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Affordability Tradeoffs Under Uncertainty Using Epoch-Era Analysis

30 September 2013

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Abstract

Acquiring defense systems in the face of urgent needs, budget challenges and scarce resources drives the need for greater process efficiency, placing focus on *designing for affordability as a requirement*. While there is progress, an efficient process for early lifecycle affordability tradeoff that takes uncertainty into account is lacking. Methods for exploring design tradespaces have matured, but largely fall short in evaluating/selecting resilient system concepts, meaning *affordably adaptable under uncertain futures*. Affordability tradeoffs are possible, but limited to tradeoffs for current operating environments or single *point futures.* As such, it's not possible to truly evaluate system concepts for resiliency since this necessitates evaluation across many alternative futures that may unfold differently. A recently developed approach, *Epoch-Era Analysis*, provides the ability to evaluate system concepts for both multiple epochs (periods of fixed context and needs) and eras (ordered sequences of epochs). This research has demonstrated usefulness of Epoch-Era Analysis in time-related affordability tradeoffs, with concurrent consideration of affordability with other key decision criteria, such as performance uncertainty. Short-run and long-run impacts of decisions in the face of temporally unfolding uncertainties are explicitly addressed by encapsulating key uncertainty factors into epochs and eras. A beta-level affordability tradeoff method with case application has been developed in this one-year research study. The method enables analysis of affordability in the face of changing contexts and needs (epochs) in short-run and long-run alternative futures (eras). In support of early lifecycle affordability tradeoffs, the method supports decision-makers faced with choosing among multiple alternative system concepts to answer the question, *Which system concept delivers highest capabilities at cost over time, taking into account potential shifts in context (e.g., policy change, technology availability) and needs (e.g., change in mission)?*

Keywords: affordability, design tradespaces, trade-offs, uncertainty, epoch-era analysis

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Executive Summary

Acquiring defense systems in the face of urgent needs, budget challenges, and scarce resources drives the need for greater process efficiency. A recent strategy to address these challenges focuses on designing for affordability as a requirement. While there is progress, an efficient process for early lifecycle affordability tradeoff that takes uncertainty into account has been lacking.

Methods for exploring design tradespaces have matured, but largely fall short in evaluating/selecting resilient system concepts, meaning *affordably adaptable under uncertain futures*. Affordability tradeoffs are possible but limited to tradeoffs for current operating environments or single point futures. As such, it's not possible to truly evaluate system concepts for resiliency because this necessitates evaluation across many alternative futures that may unfold differently. A recently developed approach, Epoch-Era Analysis, provides the ability to evaluate system concepts for both multiple epochs (periods of fixed context and needs) and eras (ordered sequences of epochs). Epochs and eras are generated though parameterization of uncertainty variables (e.g., available technology, missions). The approach has been applied to adaptability tradeoffs in several case studies.

This research has demonstrated usefulness of Epoch-Era Analysis in time-related affordability tradeoffs, with concurrent consideration of affordability with other key decision criteria, such as performance uncertainty. Short-run and long-run impacts of decisions in the face of temporally unfolding uncertainties are explicitly addressed by encapsulating key uncertainty factors into epochs and eras. A beta-level affordability tradeoff method with case application has been developed in this one-year research study. The method enables analysis of affordability in the face of changing contexts and needs (epochs) in short-run and long-run alternative futures (eras). Expected impact is a means for improving decisions in designing for affordability as a requirement in support of better buying power, ultimately yielding benefits to both warfighters and taxpayers. The ability to perform affordability tradeoffs early in the lifecycle, where forward-looking uncertainty is highest, is essential to meeting this goal.

In support of early lifecycle affordability tradeoffs, the proposed method empowers decision-makers faced with choosing among multiple alternative system concepts to answer the question, *Which system concept delivers highest capabilities at cost over time, taking into account potential shifts in context (e.g., policy change, technology availability) and needs (e.g., change in mission)?*

This research project has made progress in addressing the two challenges identified in the literature review and conversations with selected experts. The first

challenge is lack of an accepted definition of affordability. The research resulted in a proposed definition for affordability and affordable design solution, and proposed affordability analysis as identification of solutions that remain affordable in short run and long run. The second challenge is lack of metrics with systematic framework. The research resulted in a proposed method, incorporating Multi-Attribute Tradespace Exploration (MATE), Epoch-Era Analysis (EEA) and Multi-Attribute Expense (MAE). The method was applied to a demonstration case for a Next-Generation Combat Ship (NGCS).

The research resulted in a published paper for the 2013 Naval Postgraduate School Acquisition Research Symposium and the submission of a paper abstract for a future conference (accepted).

Affordability Tradeoffs Under Uncertainty Using Epoch-Era Analysis

Literature Review

This section presents a review of selected literature for key affordability concepts and motivations for design for affordability. As various research methods have been used to frame affordability as a new construct within systems engineering, their effectiveness or deficiencies in managing cost and schedule reductions is discussed. Finally, emerging methods are introduced as possible approaches for enabling the design for affordability through explicit considerations of time dependencies and uncertainty during early-phase decision-making.

Rising Cost Growth and Shrinking Defense Budgets

In recent decades, the cost growth of defense weapon systems has been escalating (Department of Defense [DoD], 2013), posing ever-greater obstacles to the defense acquisition process. Despite numerous successes, historical records have shown that many programs have been plagued by massive cost overruns, schedule delays, failure to anticipate future requirements, and ultimately unrealized capabilities (Cordesman & Frederiksen, 2006). These failures threaten the economic feasibility of future acquisition programs and combat readiness of the U.S. military in the long run.

Many investigations have been conducted into major causes of cost and schedule growth in defense acquisition. A 2009 report by Porter et al. has narrowed the causes to two main categories: weaknesses in management visibility, direction, and oversight; and weaknesses in initial program definition and costing (Porter et al., 2009). The second category encompasses failures in systems design and early-phase planning, as well as unrealistic cost estimates. Specific causes within this category may include failure in eliciting or anticipating stakeholder requirements, use of immature technologies, inadequate systems engineering, and inefficiencies resulting from schedule compression. Shrinking defense budgets over the years may also render many acquisition programs unaffordable in future. Recent annual budgets have shifted in scope and focus as they attempt to reduce acquisition costs, make better usage of resources, and achieve better buying power (Office of the Under Secretary of Defense [Comptroller], 2013). Defense budgets of 2010 and 2011 were primarily allocated to the termination of weapons programs experiencing high cost and schedule overruns, while the budgets of 2012 and 2013 have shifted to refining defense business operations. These budgets aim to achieve more lean acquisition programs with reduced overhead and support costs. Most significant

among these refinements is the implementation of the Better Buying Power (BBP) initiative (Carter, 2010a), aiming to restore affordability through pursuing greater efficiencies and responsiveness in acquisition.

The BBP initiative offers guidance to the acquisition community for obtaining greater efficiency and productivity in defense spending. Apart from recommending strategy-driven changes in labor force structure and modernization, it emphasizes the more disciplined use of resources. Central to the streamlining of business operations is the principle of targeting affordability and controlling cost growth in acquisition programs. With rising cost growth and shrinking defense budgets, Congress and policymakers are compelled to mandate affordability as a requirement at all milestone decision points of program development (Carter, 2010a, 2010b).

Introduction of Affordability in Defense Acquisition

Following the BBP initiative and the budgetary realities facing the defense industry, Dr. Ashton Carter, then Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]), issued the memorandum *Better Buying Power: Guidance for Obtaining Greater Efficiency and Productivity in Defense Spending* in 2010 to target affordability and control cost growth (Carter, 2010a, 2010b). Subsequently in 2012, Under Secretary of Defense Frank Kendall launched the Better Buying Power 2.0 initiative, an update to the original effort. As such, affordability must be explicitly considered during the system design and architecting phases. These memorandums prescribe high-level guidelines for improving effectiveness in resource usage for delivering capabilities. Guidelines include mandating affordability as a requirement; setting an affordability target as a Key Performance Parameter at Milestone A; and at Milestone B, establishing engineering trades showing how each key design feature affects target cost.

Focusing on Guideline I, affordability has now become a design requirement due to multiple instances of failure in delivering expected technical performance, increased costs and schedule delays beyond program estimates, and altering of requirements during program execution (Government Accountability Office [GAO], 2011, 2012, 2013). With explicit considerations of affordability early in and throughout the acquisition process, streamlining decisions is imperative to achieving better buying power (USD[AT&L]), 2013)

Recent Definitions of Affordability

With affordability mandated as a requirement, it has become increasingly prominent within the DoD and defense systems community. The 2010 Carter memorandum (Carter, 2010a, 2010b) defines affordability as conducting a program at a cost constrained by the maximum resources the Department can allocate for that capability. The International Council on Systems Engineering (INCOSE) defines

affordability as “the balance of system performance, cost and schedule constraints over the system life while satisfying mission needs in concert with strategic investment and organizational needs” (INCOSE, 2011). The National Defense Industrial Association (NDIA) defines affordability as “the practice of ensuring program success through the balancing of system performance (KPPs), total ownership cost, and schedule constraints while satisfying mission needs in concert with long-range investment, and force structure plans of the DOD” (NDIA, 2011). The *Defense Acquisition Guidebook* (DAG) defines affordability as “the degree to which the life-cycle cost of an acquisition program is in consonance with the long-range modernization, force structure and manpower plans of the individual DoD Components, as well as for the Department as a whole” (DoD, 2011, Section 3.2).

As evidenced by this set of definitions, the concept of affordability not only incorporates cost, but also schedule, performance, lifecycle, and all of these things relative to a larger set of possible investments. An affordable system is cost effective on its own, and relative to a larger system investment portfolio, in delivering value to the customer and relevant stakeholders. Affordability is enhanced if the system is capable of satisfying possible changing mission requirements over the system lifecycle. Consequently, a system developed without consideration for affordability is one that has been designed as a point solution in isolation, to meet a specific need at a specific time, possibly requiring the procurement of an entirely new system when customer needs evolve (Bobinis, Haimowitz, Tuttle, & Garrison, 2012). While these definitions contain the vital elements that constitute affordable systems, they do not specify how the cost of a capability should be measured and evaluated (Tuttle & Bobinis, 2012). This raises the question of how affordable solutions can be compared against one another during Milestones A and B for the purpose of a trade study or to make a contract award.

Current Ways of Understanding Affordability

One way of framing the affordability paradigm currently is through the Affordability Triangle shown in Figure 1 Conceptualized by Tuttle and Bobinis (2012), it depicts the relationship among capabilities, performance, schedule, and budget. The triangle shows that capabilities form the baseline of any acquisition process and that it is important to first establish the military need and identify how it fits within the existing defense portfolio. This process is conducted early in the Materiel Solutions Analysis Phase. After fixing the required capability, the affordability decision criteria are then based on the secondary elements of performance, budget, and schedule. These elements form the main components of affordability, and establishing a framework based on them ensures its compliance with common definitions. The balance of performance, budget and schedule considerations constitutes a standard engineering trade study.

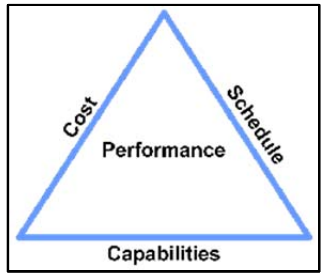

Figure 1. The Affordability Triangle
(Tuttle & Bobinis, 2012)

To transform this process to a system affordability trade study, Tuttle and Bobinis (2012) recommend the extension of the system's time horizon, as well as the inclusion of all cost elements and program increments. Based on current definitions of affordability and the elements contained within the triangle, they proposed the extraction of the following affordability components:

- Required Capabilities
    - Identify the required capabilities and the time phasing for inclusion of the capabilities
- Required Capabilities Performance
    - Identify and specify the required Measures of Effectiveness (MOEs) for each of the capabilities
    - Define time phasing for achieving the MOEs
    - Identify and specify Measures of Supportability (MOSs)
    - Define time phasing for achieving the MOSs
- Budget
    - Identify the budget elements to include in the affordability evaluation.
    - Time-phased budget, either for each of the budget elements, or as the total budget (Tuttle & Bobinis, 2012, p.7)

Tuttle and Bobinis illustrated the purpose of these affordability components through an example depicted in Figure 2. One or more of the affordability elements of capabilities, performance, schedule, or budget is designated as the decision criteria that will be used to perform engineering trade studies or decision-making. The remaining affordability elements that are not designated as decision criteria will become specified constraints.

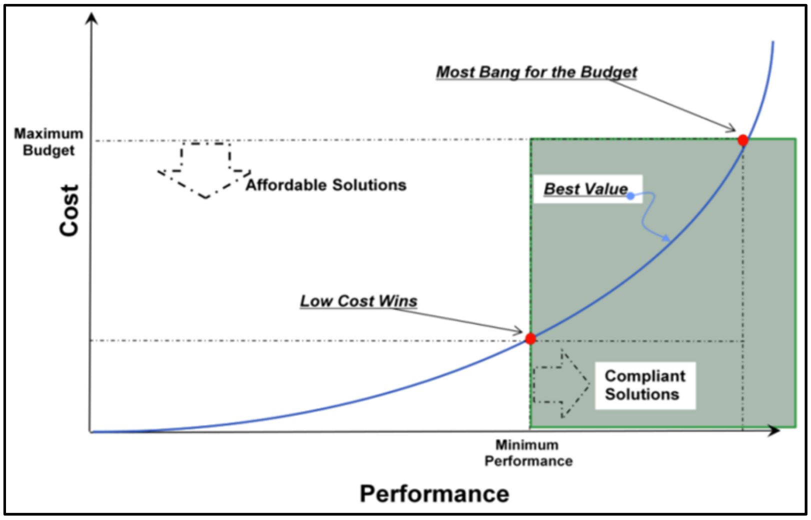

Figure 2. Determining Affordable Solution
(Tuttle & Bobinis, 2012)

In this notional example, capabilities and schedule are fixed as constants. This results in a relatively straightforward tradeoff between cost and performance, as either can become the decision criteria while the other becomes the constraint. The maximum budget and the minimum performance thresholds are identified and they are reflected as horizontal and vertical lines on the cost and performance axes, respectively. Design solutions below the maximum budget line are considered affordable within the context of the definition in the 2010 Carter memorandum (Carter 2010a). Solutions to the right of the minimum performance line will at least satisfy all stakeholder requirements, and they are considered as technically compliant solutions. The green rectangle on the graph is formed by the two threshold lines and represents the region containing solutions that meet the minimum performance requirements and are within the maximum budget.

The blue curve on the graph is another notional construct that connects all solutions that have the "best value." These solutions are considered Pareto optimal, as they provide the best possible performance achievable given the minimum cost. If cost is set as the decision criteria, the "Low Cost Wins" solution will be selected because it requires the lowest cost expenditure for meeting the minimum performance requirements. However, if the decision criterion is performance, the "Most Bang for the Budget" solution will be selected. The tradeoff for high performance is that the entire budget would be expended. As such, affordable and Pareto optimal solutions in this notional example lie along the blue line in the green rectangle.

Through this example, Tuttle and Bobinis (2012) demonstrate that designating the main affordability elements as either decision criteria or constraints could facilitate the identification of affordable solutions for a system or a program.

They also suggest that system or program affordability trade studies can be performed more accurately if the budget is time phased. While the maximum budget in Figure 2 is shown as a single number, the budget can actually be divided and illustrated as an annual budget for a sequence of fiscal years (Tuttle & Bobinis, 2012). With a time-phased budget, it will be easier for system architects and stakeholders to identify the years during which the program is affordable or unaffordable. Similarly, capabilities and performance can also be time phased, and their requirements for a particular time frame may not be met in the context of an insufficient budget.

To enable the conduct of system or program affordability trade studies, Tuttle and Bobinis also analyze the lifecycle cost (LCC) of a typical program and break it down into different categories, namely research development testing and evaluation (RDT&E) cost, procurement cost, military construction (MILCON) cost, operations and maintenance cost, and finally, military personnel (MILPERS) cost. With the integration of time phases, the cost of a system can be calculated as the sum of all colors of money across all time increments. The equation for the system cost can be written as such:

$$System\ Cost\ B_i = \sum_{j=1}^{N} B_{i,j} \tag{1}$$

where

$B_{1,j} = RDT\&E\ Cost\ of\ Increment\ j$

$B_{2,j} = Procurement\ Cost\ of\ Increment\ j$

$B_{3,j} = Milcon\ Cost\ of\ Increment\ j$

$B_{4,j} = Operations\ \&\ Maintenance\ Cost\ of\ Increment\ j$

$B_{5,j} = Military\ Personnel\ Cost\ of\ Increment\ j$

$i = 1\ or\ 5$ for a single budget element or the total budget respectively

$N =$ number of program increments, depending on the number of time phases

This is similar to the approach formulated by Alter (2011) illustrated in Figure 3, which aims to drive affordability considerations by breaking down total ownership costs (TOC) into their constituent costs. This is followed by a further breakdown to subsystem cost components, plotted on a graph with three dimensions. The subsystems are first plotted based on their TOC and their “ease of capture” in terms of room for further cost reduction. The third dimension is given by the size of the point denoting each component, which can represent a “different color of money,” such as operations and support cost. As such, areas with potential for cost reductions can be identified quickly, facilitating affordability considerations in the

design process. An understanding of the cost breakdown also helps the system architect to identify areas in which overhead and support costs can be reduced in order to mitigate overall program cost growth. This principle is reinforced by the Carter memorandum (Carter, 2010a), which states "the ability to understand and control future costs from a program's inception is critical to achieving affordability requirements."

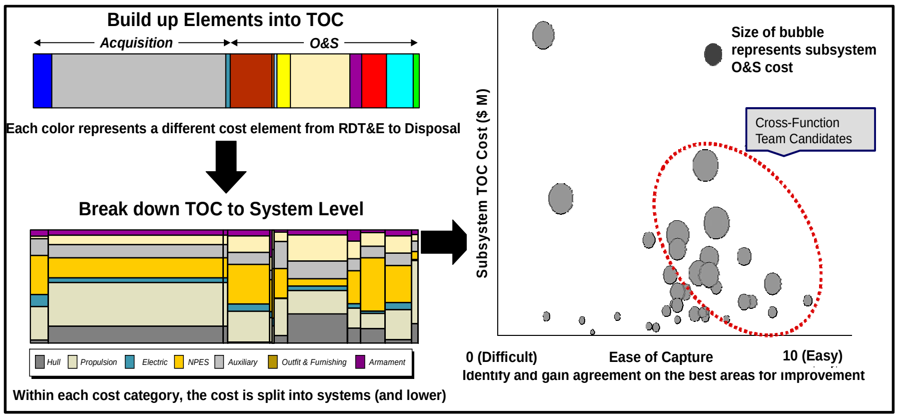

Figure 3. Breakdown of TOC Into Subsystem Costs and Identifying Areas for Improvement
(Alter, 2011)

Addressing Affordability as a Requirement

Affordability analysis and assessments have grown in importance as both government bodies and industry are forced to consider the economics of system development in the face of declining defense budgets. A multitude of quantitative methods are available and have been applied to several affordability case studies within the defense industry. Some of these methods include interval cost estimation and system lifecycle analysis, used to perform affordability analysis on a number of programs owned by the Defense Advanced Research Projects Agency (DARPA; Kroshl & Pandolfini, 2000).

Traditionally, cost estimates have been obtained by extrapolating historical data according to parameters such as technical complexity or concept maturity. Such estimates are often flawed and far from actual figures because they fail to capture uncertainty. Interval cost estimation circumvents this problem by deriving cost estimates with associated probabilities; this process is illustrated in Figure 4.

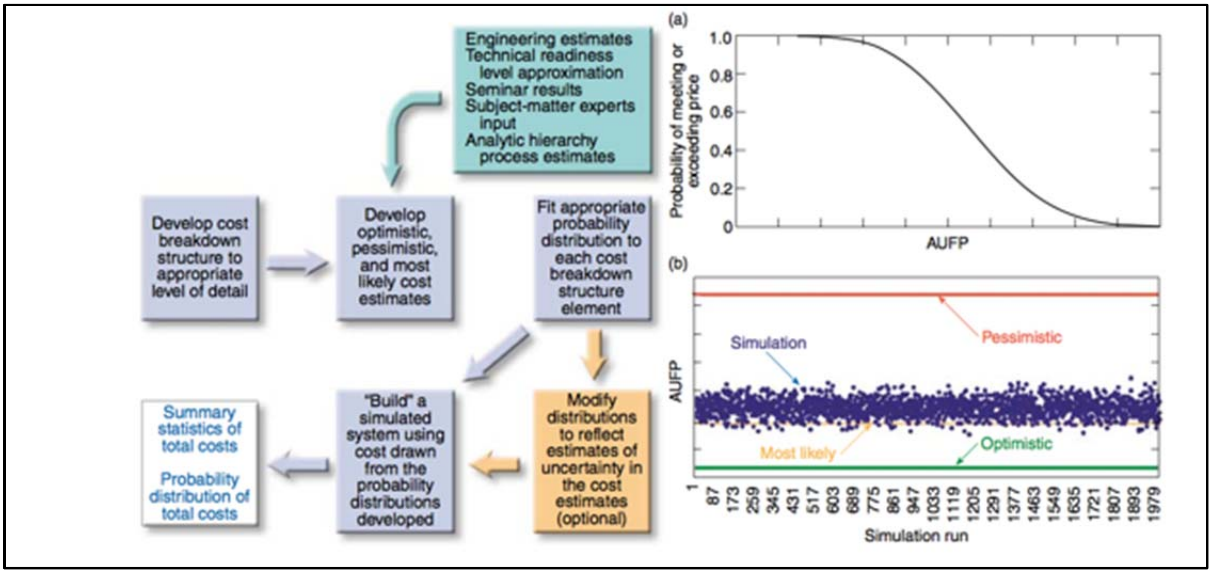

Figure 4. Interval Cost Estimation Process and Its Generated Results
(Kroshl & Pandolfini, 2000)
Note. Blue indicates the main path, orange indicates optional elements, and green indicates data sources.

The process begins by breaking down the total cost into their constituent costs or different "colors of money", followed by developing optimistic, pessimistic, and most-likely cost estimates based on expert opinion or other relevant parameters. Each cost element is then associated with a probability distribution, which may be modified to reflect uncertainty in cost estimates. Finally, all constituent costs with their assigned probability distributions are aggregated to obtain summary statistics and a probability distribution for the total cost. As such, interval cost estimation helps to build up a stochastic cost model that captures uncertainty in a systematic and traceable manner. Results from this process include a probability curve that illustrates the probability of a cost metric meeting or exceeding a price established in the affordability requirement, as well as a distribution of probabilistic cost estimates bounded by pessimistic and optimistic thresholds. This helps in deriving realistic cost estimates and determining whether the program of interest remains within the affordability requirement.

System lifecycle analysis is much like the process described by Tuttle and Bobinis (2012), in which cost or performance can be set as the decision criteria while the other is left as the constraint. Metrics used in this analysis are drawn from engineering economics and financial analysis, and they include net present value (NPV), internal rate of interest (IRR), and learning curve functions. The calculation of these metrics can provide decision-makers with useful information during the earliest studies of advanced concepts.

Affordability and Ilities

With the recent emphasis on designing for affordability as a requirement in acquisition management, various systems engineering approaches have been applied to design systems or programs that are more manageable under explicit cost, schedule, and performance constraints. However, current processes for performing early lifecycle affordability tradeoffs remain underdeveloped. In recent strategies, affordability tradeoffs have been limited to static tradeoffs of systems in current operating environments or in single point futures. Given that systems exist in a dynamic and uncertain world, designing for affordability not only necessitates new methods capable of evaluating systems across many possible alternative futures, but also a new philosophy for treating the affordability paradigm.

Since the application of ilities (reliability, flexibility, robustness, etc.) in systems engineering can potentially lead to positive results in the design process, affordability may be treated as an ility that can drive the design of more affordable yet technically sound architectures. With affordability as an ility, advanced systems engineering methods like tradespace exploration may be applied in the selection and identification of affordable designs (Schaffner, Wu, Ross, & Rhodes, 2013).

Tradespace Exploration

Tradespace exploration has been extensively utilized in systems design and architecting to facilitate the identification and selection of architectures that best fit stakeholder requirements. The full tradespace of a system is spanned by all its possible design alternatives, and it represents the mapping of design variables to attribute trades. Enumerating existing design variables generates all possible alternatives, and expanding the tradespace requires the generation of either new design variables or reconfigurations of existing combinations of variables (Ross, Hastings, Warmkessel, & Diller, 2004). Concurrently, a validated model for the system is also constructed based on logical assumptions and stakeholder preferences. After enumeration and evaluation, the tradespace is then typically bounded by the parameters of utility and cost to yield the solution space. The Pareto frontier of these design points is then established and traces Pareto subset solutions with the best tradeoffs among attributes and provides the highest utility for a fixed cost.

The process of tradespace exploration allows comparison of many designs on a common, quantitative basis, and it structures the design and solution space to reflect stakeholder values. As thousands of designs have to be evaluated, tradespace exploration requires computational models to facilitate the assessment and identification of "best" or "optimized" solutions along the Pareto front, thereby avoiding fixation on local point solutions. Uncertainties in cost, schedule, and

performance are also accounted for in the model through a variety of quantitative methods. Beyond establishing the Pareto front, tradespace exploration also entails the search for patterns and structures emerging within dominated regions of the tradespace (Ross, 2006) and can be further analyzed in terms of the spatial distribution of points or clusters within the solution space. Tradespaces can also become dynamic when changes in utilities and costs over time are considered. A sample tradespace is shown in Figure 5 (Ross, 2006), which also places the various types of trades into perspective: (1) point solution, (2) Pareto subset, (3) Pareto frontier, (4) full tradespace, and (5) dynamic tradespace.

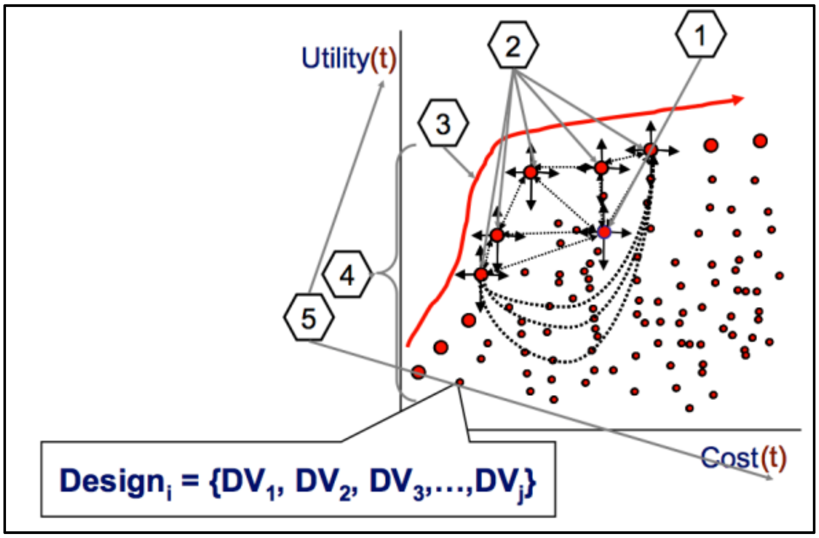

Figure 5. Tradespace Depicting Different Trade Types
(Ross, 2006)

The tradespace exploration paradigm can facilitate the system design generation, evaluation, and selection process, and utilization of resources to meet evolving stakeholder requirements. Tradespace exploration has already been applied to select best designs for numerous space systems and even best options for policy robustness. As such, dynamic system tradespaces with consideration of temporality may be used to perform affordability tradeoffs early in the lifecycle and demonstrate changes in costs as major decision parameters and time to completion are varied.

Decision-making frameworks are often applied within the tradespace exploration process to expedite the identification and selection of “best” or “optimized” designs. Multi-Attribute Utility Theory (MAUT) is one such framework within decision analytics that may be used to perform affordability tradeoffs as it allows the capturing of stakeholder preferences for simultaneous multiple objectives (Keeney & Raiffa, 1993). It uses mathematical representations to capture complex tradeoffs and interactions among the attributes that have been translated from

articulated design and risk preferences (Ross, 2003). Multi-Attribute Tradespace Exploration (MATE) is a conceptual design method that applies MAUT to model and simulation-based design (Ross et al., 2004).

MATE resolves conflicting and subjective evaluations of decision-making processes by combining various single-attribute utility functions for every attribute of interest into a single function that quantifies how a decision-maker values different attributes relative to one another. The MATE process maps the design and attribute space of the system to the solution space, which is typically defined by the parameters of aggregated utility and cost. The MATE process, illustrated in Figure 6, culminates in the generation of a tradespace that allows thousands of design alternatives to be compared on a common, quantitative basis. As such, MATE provides decision-makers a prescriptive framework for selecting preferred designs that can be carried forward for more detailed sensitivity analysis and eventually development.

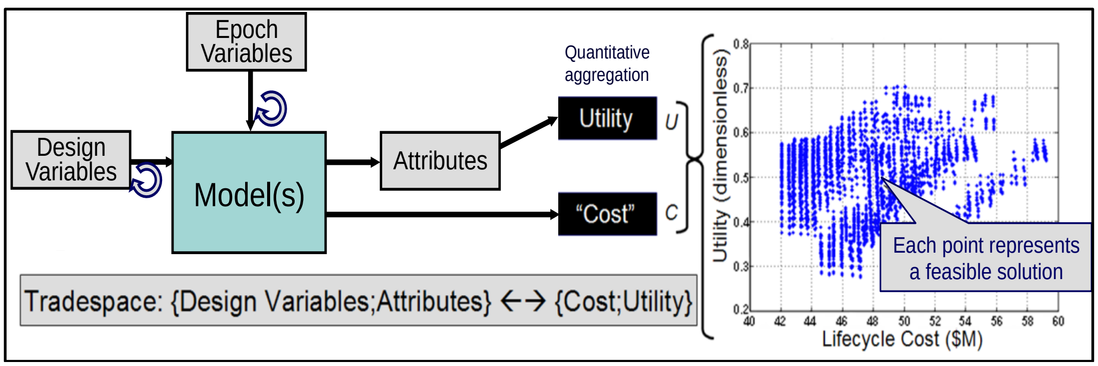

Figure 6. Multi-Attribute Tradespace Exploration Framework
(Ross, 2006)

MATE provides a method for identifying affordable systems, forcing alignment of solutions to needs, facilitating cross-domain socio-technical conversation, and discovering compromise solutions. By explicitly considering cost and schedule constraints, affordability tradeoffs may be performed through a complete exploration of the tradespace, and affordable solutions may be identified in the solution space.

Epoch-Era Analysis

Epoch-Era Analysis (EEA) is a computational scenario planning approach (Roberts, Richards, Ross, Rhodes, & Hastings, 2009; Ross & Rhodes, 2008) that can be used for the analysis of systems operating in dynamic environments. EEA considers changes in needs and context in tradeoffs, along with the system itself. One of the advantages of EEA is that it allows for consideration of temporality and exogenous impacts in the analysis of system capabilities for cost. Often shifts in contexts occur more frequently than system development timelines, such as

changes in budgets, administrations, and warfighter needs. Figure 7 illustrates this mismatch in terms of development phase, possible transitions in the system, and “epoch” time periods of fixed context (includes technologies and policies) and needs. During the lifecycle, there are various system changes (i.e., “transitions”) that may occur, resulting in fluctuations that feed back into the program.

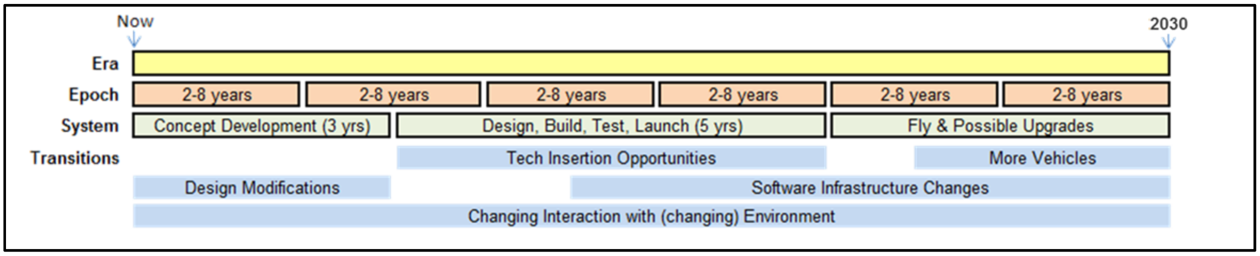

Figure 7. System Lifecycle Phases, Transitions, Epochs, and Eras

To effectively evaluate the impact of dynamic variation in costs with tradeoffs in decision parameters and time to completion, EEA may be applied to enable designing for affordability. EEA has been developed to consider and clarify the effects of changing contexts and needs over time on the perceived value of a system in a structured manner (Ross, 2006; Ross & Rhodes, 2008). Instead of discretizing the system lifecycle according to traditional system milestones, EEA discretizes the lifecycle according to impactful changes in the operating environment, stakeholders, or the system itself, through the constructs of epochs and eras.

An epoch is a time period of fixed contexts and needs under which the system operates, and it can be characterized using a set of variables that define any factor, such as technology level and supply availability, which impacts the usage and value of the system. An ordered sequence of epochs constitutes an era and describes the potential progression of contexts and needs over time. Any futures relevant to system performance or costs can be described through assignments to the available epoch variables, providing a form of computational scenario planning.

Epoch variables define the context and time that the system may be operating in. They can affect the usage and value of the system and may be in the form of weather patterns, political scenarios, financial situations, operational plans, and availability of other technologies. Appropriate epoch variables for an analysis will include exogenous uncertainty factors that will affect the perceived success of the system (Ross, 2006). Figure 8 shows the temporal progression of a system as needs and contexts change. The vertical columns represent the epochs that are time-ordered to form an era. The different colors of these epochs represent changes in context. The horizontal bands capturing the minimum and desired expectation levels for that epoch represent expectations (needs). Contexts and needs can

change independently of one another as shown by the different horizontal bands. The system can potentially exhibit a different ility in each context.

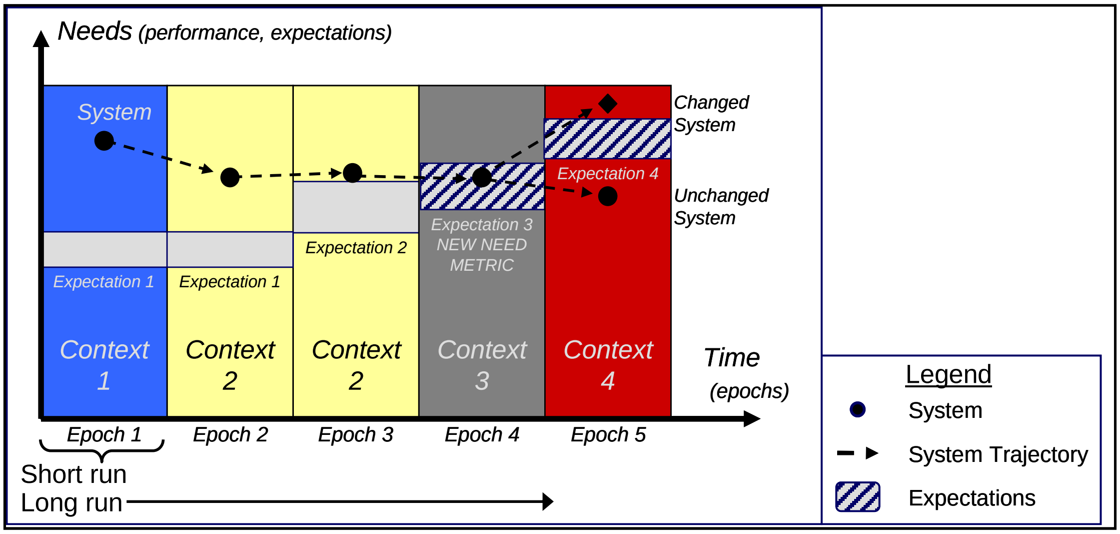

Figure 8. System Needs Versus Expectations Across Epochs of the System Era
(Ross, 2006)

Initially in Epoch 1, the system exceeds the needs of stakeholders. Later in Epoch 2 and Epoch 3, the context and needs change respectively. In these cases, the system still meets expectations and displays value robustness. The shift to Epoch 4 represents a new need of the system, which the system satisfies, displaying versatility. In Epoch 4, the system does not exceed all the needs, but does meet the minimum required level and remains successful. Finally, the shift to Epoch 5 represents the need for a changeable system. As seen, the system is not robust or versatile to new needs and context, and requires change in order to remain successful (Beesemyer, Ross, & Rhodes, 2012).

As demonstrated by this notional system trajectory, EEA can structure consideration of changing contexts and needs on system success, and suggest strategies for how to sustain value in both the short run and the long run. As such, EEA may be used in conjunction with MATE to help in the search for designs that are affordable across many discrete epochs and design for ilities in systems (Ross, 2006). This approach provides an intuitive base upon which to perform analysis of value delivery over time for systems under the effects of changing circumstances and operating conditions, an important step to take when evaluating large-scale engineering systems with long lifespans.

Figure 9 illustrates how alternative eras can be constructed from the enumerated epochs in time-ordered sequence. Eras can be constructed either by selecting pre-defined, “hand-picked” epochs to fit imagined future scenarios of

interest, or eras can be constructed in a combinatorial, logic-based automated fashion. Automated era construction can be random, constrained by a given set of conditions, or can be iterative, so that the selection of each subsequent epoch depends on the preceding one. The sequential ordering of selected epochs produces an emergent path dependence of value over time for each system alternative (i.e., the optimal design strategy given an uncertain future may depend on the order of future events).

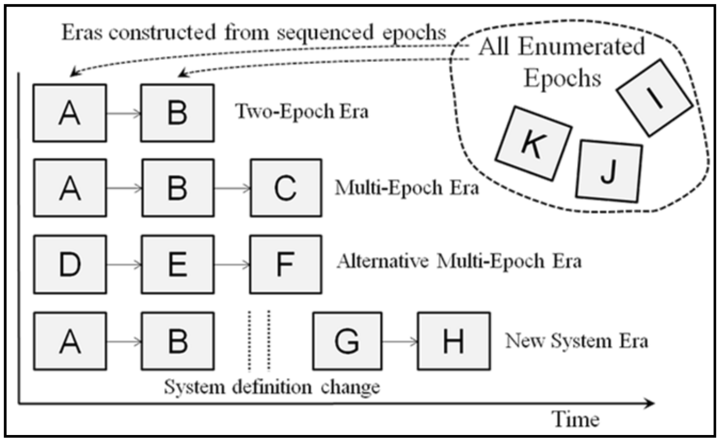

Figure 9. Alternative Eras Constructed From Enumerated Epochs
(Rader et al., 2010)

Epoch-Era Analysis is first used to gather performance and uncertainty information of selected alternative system concepts operating through different epochs and eras. This is accomplished through enumeration of possible epochs (exogenous uncertainties), basic performance models (to evaluate the performance of alternative concepts within particular epochs), and related analyses (“multi-epoch analysis” and “era-level analysis”).

Figure 10 shows the enumeration of epochs for an example of a U.S. Coast Guard (USCG) Offshore Patrol Cutter program, in which five selected epoch categories have one or more associated descriptors (or variables), each having units and ranges. Constraints are also noted.

Epoch Descriptor Category	Epoch Descriptor	Units	Range	Constraints
Technology	Availability of VUAV Technology	Level	Small-Large	Requires hangar storage
	C4ISR Racks	Level	Small-Large	Original design space, weight, and power
	Small Boat Size	ft	24-35	C4ISR Info to/from cutter remain same
Policy	Engine Emmissions Rating	Tier	2 to 4	Weight
	Discharge Copper Content	Level	Low-Medium-High	Maintain original system service life
	SCIF Size	Level	Low-Medium-High	Location near operational spaces
Budget	Project Baseline	%	-20	
Systems of Systems	Operational Availability	Dimensionless	0.85-0.92	Major equipment remains same
	Range Increase	%	5 to 20	Same operational conditions
	Helicopter Weight Increase	%	5 to 50	Size less than HH-60
Missions	Ice Region Use	Level	Low-Medium-High	Floating ice capability only
	Equipment Storage	ft^3	Small-Large	Storage only
	Water/Food Storage	% Increase	5 to 20	Same operational conditions

Figure 10. Enumeration of Epochs Example for Coast Guard Offshore Patrol Cutter

(Schofield, 2010)

The two types of analyses within EEA each provide unique insights into the impact of uncertainty and dynamics on the value (capabilities at cost) produced by a system. Multi-Epoch Analysis is an approach for identifying systems robust to exogenous uncertainties involving contexts and needs (Fitzgerald & Ross, 2012). This is accomplished through enumeration of possible epochs that might be encountered by a system. These epochs encapsulate a particular “point sampling” of uncertain futures. Analysis can be done looking across all of these point futures to identify alternatives that perform well (i.e., deliver high utility at low cost), that is, alternatives that are robust to changes in contexts and needs (Ross, Rhodes, & Hastings, 2009). This type of analysis calculates metrics, such as Normalized Pareto Trace (NPT), which represents the fraction of epochs in which a given design alternative is considered cost-utility efficient, as shown in Figure 11.

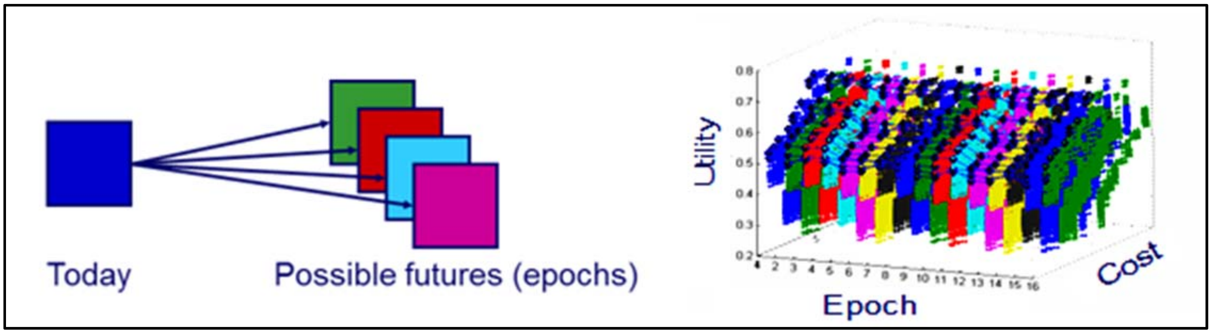

Figure 11. Epochs as Alternative "Point" Futures (l) and Multi-Epoch Analysis (r)

Multi-Attribute Expense (MAE)

Designing for affordability is not only concerned with the monetary lifecycle cost of a system, but also its “schedule” of development and its responsiveness to emerging needs (INCOSE, 2011). However, such temporal considerations are often difficult or impossible to represent in dollars and these different colors of money may also be spent with differing degrees of ease. This is not easily captured by general utility. A possible solution to affordability analysis is the use of the Multi-Attribute Expense (MAE) function (Diller, 2002), which aggregates these different types of dollar budgets. MAE is formulated similarly to a MAU function (Keeney & Raiffa, 1993), with the utility function replaced by an expense function *E*(*X*).

$$KE(X) + 1 = \prod_{i=1}^{N} [Kk_i E_i(X_i) + 1] \tag{2}$$

Expense refers to system aspects that the designer wants to keep at low levels, a concept akin to the notion of negative utility. Expense is focused on “what goes into a system” in contrast to utility, which is focused on “what comes out of a system.” Quantified on a 0 to 1 scale, an expense level of one denotes complete dissatisfaction, and an expense level of zero denotes minimal dissatisfaction. As such, a stakeholder typically demands maximal utility and minimal expense in an ideal design.

Like MAU, an MAE function requires careful construction through stakeholder interviews to elicit informed responses and aggregate preferences to capture articulated value. As MAE is a dimensionless, non-ratio scale metric, an entity with twice the MAE number over another does not imply that it is twice as expensive in terms of monetary value. Since temporal elements like schedule constraints and time-to-build have extensive leverage on the different colors of money, the MAE can be extended to affordability applications in federal acquisition processes. Instead of comparing monetary costs against utility, EEA and MATE may be modified to

compare MAE against MAU in order to perform an affordability-driven analysis that captures the elements of both time and costs.

Therefore, MATE, EEA, and MAE can be combined to yield an enabling method for making effective comparisons of benefits and costs across a range of alternative futures (Schaffner et al., 2013). By explicitly accounting for cost, schedule, and performance requirements over time, the method is able to account for system changes due to shifts and perturbations, manage lifecycle differences between subsystem components, evaluate feedback, and be adaptive to evolving system behaviors. As affordability is a concept evaluated over time, such a method can provide structured options for improvement to enable enhanced design for affordability.

METHOD FOR AFFORDABILITY TRADEOFFS UNDER UNCERTAINTY

The outcome of this research is a nine-process method, applied in the selected case, which extends from prior research at the Massachusetts Institute of Technology (MIT). The purpose of the method is to perform affordability tradeoffs under uncertainty. The overall structure of the proposed method consists of nine processes, which are grouped into three distinct parts: information gathering (Processes 1 through 3), alternatives evaluation (Process 4), and alternatives analysis (Processes 5 through 9). A graphical representation of the method is shown in Figure 12.

The information-gathering portion, Processes 1 through 3, consists of defining the context and problem statement, stakeholders and respective needs, and contextual variables. The alternatives analysis portion, Processes 5 through 9, compares the dynamic properties of potential designs across the potential futures that the system may encounter. These two main portions of the proposed method are bridged by Process 4 (Design-Epoch Tradespaces Evaluation), which can provide feedback to decision-makers and stakeholders, creating an opportunity to revisit the information gathering processes. Process 4 also provides a cursory analysis of potential designs in preparation for the more in-depth alternatives analysis in the second half of the method.

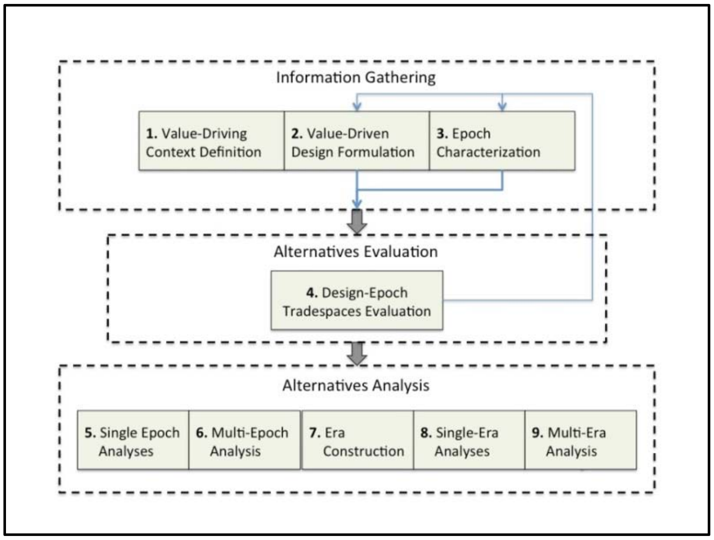

Figure 12. A Graphical Overview of the Gather-Evaluate-Analyze Structure of the Method

The processes of the proposed method, with brief descriptions of the activities involved, are as follows:

Process 1: Value-Driving Context Definition

The first process of the proposed method involves development of the basic problem statement. The stakeholders are identified, relevant exogenous uncertainties are elicited, and an initial value proposition is formed. The resources available to each stakeholder are examined along with the associated uncertainties.

Process 2: Value-Driven Design Formulation

The second process begins by defining the needs statements for all stakeholders, which become the attributes of system performance, along with utility functions describing each stakeholder's preference for each attribute. The stakeholder resources statements are also elicited (with corresponding expense functions), which then become the attributes of the system's expense function. The system solution concepts are proposed from past concepts or expert opinions. These concepts are decomposed into design variables of the system.

Process 3: Epoch Characterization

In this process, the key contextual uncertainties are parameterized as epoch variables, and possible future contexts are identified. Uncertainties in stakeholder needs are elicited. Uncertainties in resource supply and availability are also identified, along with changes to stakeholder preferences on resource usage.

Process 4: Design-Epoch Tradespaces Evaluation

This process utilizes modeling and simulation to map the design and epoch variables to system performance attributes and expense attributes. Stakeholders' utility and expense functions are then used to generate the MAU and the MAE for each design, within each epoch.

Process 5: Single Epoch Analyses

This process includes the analysis of MAU and MAE of alternatives within particular epochs, including designs graphically compared on an MAU versus MAE scatterplot for any given epoch (time period of fixed operating context and stakeholder needs). Within-epoch metrics, such as yield, give an indication of the difficulty of a particular context and needs set for considered designs.

Process 6: Multi-Epoch Analysis

After completing the traditional tradespace exploration activities of Process 5, in which the practitioner compares potential designs within a particular epoch, metrics are derived from measuring design properties across multiple (or all) epochs to give insight into the impact of uncertainties on potential designs, including evaluation of short-run passive and active strategies for affordability (i.e., efficient MAU at MAE). In addition, resource usage can be analyzed to identify designs that are robust to the factors identified in Process 3 (e.g., decreasing budgets or labor availability).

Process 7: Era Construction

This process constructs multiple sequences of various fixed duration epochs to create alternative eras, which are long-term descriptions of possible futures for the system, its context, and stakeholder needs. This process can be performed with the aid of expert opinion, probabilistic models (e.g., Monte Carlo or Markov models), and scenarios of interest to stakeholders.

Process 8: Single-Era Analyses

This process examines the time-dependent effects of an unfolding sequence of future epochs (era) created in Process 7. By examining a particular series of epochs for a given length of time, decision-makers can identify potential strengths and weaknesses of a design and better understand the potential impact of path-dependent, long-run strategies for affordability.

Process 9: Multi-Era Analysis[1]

This process extends Process 8 by evaluating the dynamic properties of a system across many possible future eras, identifying patterns of strategies that enable affordability across uncertain long-run scenarios.

CASE APPLICATION AND ANALYSIS

Introduction and Background

The analysis of system affordability covers many of the aspects previously discussed, including the system development schedule, various types of expenses, and the level of those expenses in dynamic operating environments over the system lifecycle. Ideally, these factors must be balanced with the value delivery of the system, since a system providing minimal performance might be affordable but not desirable. In this case study, an established method for conceptual system design is used to consider all of these factors, augmented by several metrics introduced to cover resource-centric concerns. The first of these measures is the Multi-Attribute Expense (MAE) function, intended to aggregate stakeholder preferences on resource consumption. The second is the Max Expense metric, which gives the maximum resource expenditure for any resource across time. The third is the Expense Variability metric, which reflects the stability of resource consumption over time. The incorporation of all of these metrics enables the design method to directly inform analysts and decision-makers of the relative affordability of each potential design under consideration, whether relative to one another or to established projected budget levels.

The method developed in this research is based upon the Responsive Systems Comparison (RSC) method (Ross et al., 2008). The RSC method was developed to aid in the design of complex systems across many domains, allowing effective anticipation of future contexts and needs relevant to system design choices early in the lifecycle through the Epoch Era Analysis (EEA) approach (Ross & Rhodes, 2008). RSC has been applied to several case applications ranging from satellite systems (Ross, Rhodes, McManus, Hastings & Long, 2009) to a proposed Coast Guard replacement vessel (Schofield, 2010). The method applied in the present study is the earlier described nine-process method, focused on affordability analysis, as applied to a hypothetical Next-Generation Combat Ship (NGCS). NGCS is conceived as a larger version of the Navy's current Littoral Combat Ship (LCS) that would support air and sea operations over diverse areas of interest for the next

[1] The process is not demonstrated by the current study due to the representative nature of the analysis but is described here for completeness.

30 years. Schofield's (2010) application of the original RSC method was to a smaller naval application, the Coast Guard's Offshore Patrol Cutter (OPC). The current case draws from the design variables, attributes, and epochs from Schofield's OPC study, augmented by evaluation of outputs using the MIT Math Model. The MIT Math Model is a standard naval modeling tool regularly used by the MIT Ocean Engineering group (formerly department) for the evaluation of potential designs for naval frigates (slightly larger than the LCS).

The proposed NGCS requirements, therefore, reflect some similarity with both the OPC and LCS. For example, the OPC is designed to operate in a variety of mission areas, including ports, near shore, and open sea, with a range in excess of 8,500 nautical miles and endurance minimum of 45 days (Schofield, 2010). The LCS is designed to have a range in excess of 3,500 nautical miles and an endurance of 21 days. The NGCS that is the focus of this study, meanwhile, is required to operate in mission areas at least as varied as the OPC, have a minimum endurance of 30 days, and have a range in excess of 4,000 nautical miles. It is anticipated that the operating context of the NGCS is largely similar to that of the OPC, so many of the NGCS's contextual variables mirror those from the OPC study.

Application of the Proposed Method to the NGCS

While the OPC and LCS systems are designed for many-unit acquisitions occurring over a period of several years, the present study examines only a single unit acquisition for the purposes of demonstrating the salient points of analysis.

Process 1: Value-Driving Context Definition

The value-driving context for the OPC is made up of the value propositions as well as the key stakeholders involved in decision-making and funding. Schofield (2010, p. 82) defines the value propositions for each stakeholder as follows:

> **Project Office**: Provide a new cutter fleet that meets operational requirements within a defined budget level and whose delivery coincides with the decommissioning of the current WMEC fleet.
>
> **Sponsor**: Develop operational requirements that meet the mission needs of the Coast Guard and Coast Guard user requirements.
>
> **Technical Authorities**: Ensure that the new developed system meets legacy, external constraints, and design standards with technologies that maximize capability within established risk requirements.

It is clear from the value propositions that concern for resource usage is not consistent across stakeholders; as one might expect, each stakeholder has different expectations and goals with regard to resources involved in the project. The project office specifically addresses two standard resources: budget ("defined budget level")

and schedule (“delivery to coincide with ...”). The sponsor appears to be primarily concerned with the mission needs and user requirements of the organization, and resource usage is not of primary concern. The technical authorities’ value statement includes the aspect of technological resources that enable core capabilities.

Because each of the stakeholders’ value propositions reveal the different priorities of their respective organizations, the present case of the NGCS combines the various points of view into one representative stakeholder for simplicity of analysis. This stakeholder desires to provide the new fleet of USN frigates for use in air and sea operations in a variety of operating areas. In the second process of the proposed method, interviews with this stakeholder will better reveal the relevant preferences on the usage of the resources.

Process 2: Value-Driven Design Formulation

The second process builds upon the initial system context definition by first proposing the system design concept and then eliciting the attributes desired by (as well as expense attributes of importance to) the stakeholder. Through stakeholder interviews, the attributes’ characteristics can be determined and weighted according to the preferences revealed. In this case, the weights placed on each attribute reflect the “combined” stakeholder from Process 1. Two types of attributes are delineated in the results: those attributes which represent resources that would ideally be conserved from the stakeholder’s perspective, or “expense” attributes (e.g., acquisition cost, crew size), and those attributes which represent performance that would ideally be maximized, or “utility” attributes (e.g., range, speed). The results of this activity can be seen in Figure 13.

Mission Statement:	Provide new frigate fleet for the USN.			
Objective:	Provide defense, air, and sea support across the defined mission areas.			
Attribute (Acronym)	**Units**	**Range ["worst" to "best"]**		**Weight (.1 to 1)**
Acquisition Cost (Acq.)	$ million	1500	500	0.4
Lifecycle Cost (LC)	$ million	7500	3000	0.3
Initial Operating Cap. (IOC)	year	2020	2018	0.2
Crew Size (Crew)	# persons	250	200	0.1
Displacement (Disp.)	cubic ft.	11000	4000	0.2
Range	nm	4500	10000	0.2
Speed	kts	12	25	0.1
Air Capability (Air Cap)	hrs/day	2	12	0.2
Endurance (Endr)	days	30	60	0.1
Small Boat Capability (SBCap)	#ppl-hrs/day	20	100	0.2

Figure 13. Decomposition of Mission Statement Into Attributes

The design concepts are then partitioned into potential design variables for the proposed system. To better identify the key design drivers, the relationships of

design variables to utility attributes and expense attributes are then assessed qualitatively by the values *none*, *low*, *medium*, or *high* impact, using a Design-Value Matrix (DVM) with values of 0, 1, 3, and 9 as a visual aid for this activity. Following Schofield's (2010) example of decomposing the value propositions generated in Process 1 to infer the utility attributes, the present study creates a DVM mapping the impact of design variables to the resource expenditures of the system. The impacts are assessed of each design variable on each expense attribute in addition to the utility attributes, generating the DVM shown in Figure 14.

Design-Value Mapping (Notional Values)											
Representative Stakeholder											
Expense Attributes / **Design Variables**	Length	Beam	Draft	Prop Type	Hull Material	Deckhouse Material	Defense Cabability	Helos	ASUW	AAW	**Total Impact**
Acquisition Cost	9	3	3	3	3	3	3	3	3	3	**36**
Lifecycle Cost	9	3	3	9	1	1	1	1	1	1	**30**
IOC	1	3	1	3	1	0	3	1	1	1	**15**
Crew Size	3	1	1	1	1	1	3	3	3	3	**20**
Total	**22**	**10**	**8**	**16**	**6**	**5**	**10**	**8**	**8**	**8**	
Utility Attributes											
Displacement	9	9	3	3	9	3	3	3	1	1	**44**
Range	9	3	1	9	3	1	1	3	1	1	**32**
Speed	9	3	3	9	3	1	3	1	1	1	**34**
Air Capacity	3	3	1	0	1	1	3	9	3	3	**27**
Endurance	1	3	1	3	1	1	3	3	3	3	**22**
Small Boat Cap.	3	3	1	0	1	1	3	3	3	3	**21**
Total	**34**	**24**	**10**	**24**	**18**	**8**	**16**	**22**	**12**	**12**	

Figure 14. A Design-Value Matrix Reflecting the Notional Impact of Design Variables on Attributes

Several benefits exist from creating such a DVM. First, by summing the rows and columns of the DVM, a practitioner can quickly determine which design variables have the most impact on general resource usage (in the notional example, the length and propeller type are the most impactful), as well as which resources are more sensitive to the present design choices (again, from the notional data, the Acquisition Cost is the most sensitive, followed by Lifecycle Cost and Crew Size). Generating an enhanced DVM, with both utility attributes and expense attributes, provides an expanded cost and benefit perspective on the ramifications of various

design decisions. Second, if low-impact design variables are identified (e.g., Draft, Deckhouse Material), they can be removed from the analysis to simplify the process going forward and concentrate effort on the design drivers. Finally, these impacts can be used to inform the modeling and simulation of the system necessary to evaluate system attributes in Process 4, Design-Epoch Tradespaces Evaluation.

Process 3: Epoch Characterization

After identification of the design variables, performance and expense attributes, and their corresponding relationships, the internal and external uncertainties are added into the analysis. Schofield (2010) lists the external uncertainties (in the associated categories) related to the OPC as follows:

Technology: Vertical Unmanned Aerial Vehicle (VUAV) integration; major C4ISR system upgrade; and new and more capable (size, range, personnel carried) small boats

Policy: Marine engine emission reductions; reduced copper content from shipboard systems (sea water systems); increased intelligence gathering into government-wide system

Budget: Loss of acquisition budget prior to Initial Operational Capability (IOC); increase in operational funding for increased operational usage

System of Systems (SoS): Deploying with National Security Cutters; new cutter-deployed helicopters

Missions: Support of arctic region for fisheries; adding environmental cleanup response capability; more frequent international presence particularly for peacekeeping missions

Epoch variables are generated from these uncertainties by determining the primary source of the possible changes in operating context. For instance, Schofield (2010) uses the marine engine emission reductions uncertainty in the Policy category to generate the "Engine Emissions Rating" epoch variable, which has an integer value range from 2 to 4. Due to the similarities of operating contexts and missions, the epoch variables chosen for the NGCS are a subset of those outlined for the OPC. The epoch variables chosen are shown in Figure 15, with the corresponding category, associated ranges of values, and corresponding units.

	Epoch Variable	Levels [Range]	Units
EV -- Tech	VUAV	[Small, Large]	Storage Level
EV -- Tech	Small Boat Size	[24, 35]	ft
EV -- Policy	Engine Emissions	[2, 3, 4]	(Tier)
EV -- SoS	Range Increase	[0, 10, 20]	%
EV --Mission	Ice Region Use	[Low, Med, High]	Level

Figure 15. A List of the Epoch Variables Modeled for the NGCS Context and Needs

Once each epoch variable is created, the impact of the epoch variables on each of the design variables, performance attributes, and resource attributes can then be depicted with an Epoch Descriptor Impact Matrix, similar to the DVM in Process 2. The complete Epoch Descriptor Impact Matrix with values (both notional and taken from Schofield's 2010 OPC study) is shown in Figure 16.

Epoch Descriptor Impact Matrix

	VUAV	Small Boat Size	Engine Emissions	Range Increase	Ice Region Use	Total Impact
Utility Attributes						
Range	1	1	1	9	9	**21**
Speed	1	1	9	9	3	**23**
Displacement	1	1	0	3	3	**8**
Air Capability	3	3	0	3	3	**12**
Endurance	1	1	1	9	3	**15**
Small Boat Capability	1	9	1	3	3	**17**
Total	**8**	**16**	**12**	**36**	**24**	
Expense Attributes						
Acquisition Cost	3	3	3	1	0	**10**
Lifecycle Cost	3	3	1	9	3	**19**
IOC	1	0	3	1	3	**8**
Crew Size	3	3	1	3	1	**11**
Total	**10**	**9**	**8**	**14**	**7**	

Figure 16. A Matrix Reflecting the Notional Impact of Epoch Variables on Design Variables, Utility Attributes, and Expense Attributes

Similar conclusions can be drawn as in Process 2; for example, it is clear from the sums of rows in Design Variables that Speed and Range are the utility attributes most impacted by the uncertainties, and Lifecycle Cost is the most impacted expense attribute. Conversely, the Range Increase epoch variable is the most impactful (by quite a margin) on all attributes, with Ice Region Use heavily

impacting performance. Gaining an understanding of these relationships early in the design process allows a practitioner to begin considering how a design should be oriented to cope with uncertainties, as well as to keep in mind those contexts which are especially detrimental to the utility or expense of the system, whether directly or through opportunity costs. In addition, this mapping will aid in the evaluation of designs in each epoch and era in the subsequent processes of the method.

Process 4: Design-Epoch Tradespaces Evaluation

Once the value-driving context has been defined, along with the value-driven designs (variables and attributes) and epochs, a practitioner is ready to begin evaluating candidate designs in all epochs. The evaluation of the potential designs' attributes in the case of the NGCS was achieved through use of the MIT Math Model, which is a set of mathematical relationships developed at MIT and used for over 20 years in the design of Navy frigates for academic and government studies. The model's inputs and outputs include length, beam, draft, crew size, weapon packages, and many other factors (around 50 in all). It incorporates detailed calculations of payload size, hull geometry, machinery, power and space requirements, weight, stability, and a simplified cost model. Using the model, a naval subject matter expert generated six feasible ship designs based on the design variables provided, producing the attributes of Acquisition and Lifecycle Costs, Crew Size, Range, Speed, Displacement, and IOC for the six representative NGCS designs. These attributes were combined with several others—Air Capability, Endurance, and Small Boat Capability—along with the notional impacts of the epoch variable levels from Process 3. The resulting (adjusted) attribute levels were mapped to stakeholder preferences through the use of single attribute utility functions. The utility curves for the levels of each attribute—normally captured through stakeholder interviews, but here generated through assessment of current capabilities and the concepts of loss aversion and anchoring in prospect theory (Kahneman & Tversky, 1979, 1984)—provide a single attribute utility value for each system attribute's level. The utility curves defined for all attributes in the baseline epoch are shown in Figure 17.

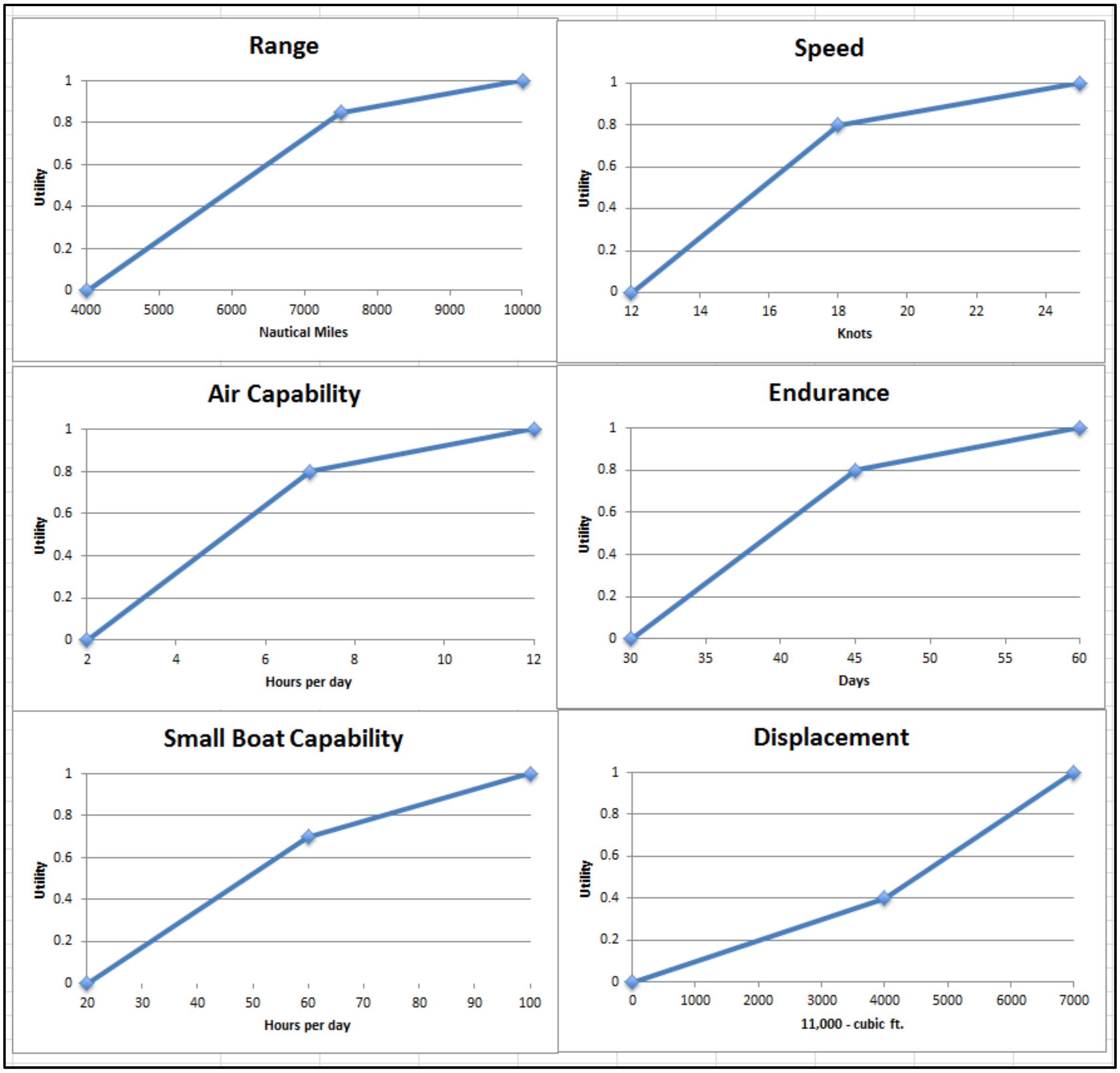

Figure 17. Single Attribute Utility (SAU) Curves on Each System Attribute

Note. The leveling off of stakeholder satisfaction/dissatisfaction occurs around levels established by previous systems.

All of the single attribute utility values are then aggregated into a Multi-Attribute Utility (MAU) value for each design point. Two key assumptions are made during this step: preferential independence among attributes and utility independence among attributes. If each attribute of the system contributes independently to utility, then the swing weights (relative ranking of an attribute's importance when it is at its best values and all others are at their minimally acceptable values) on each attribute sum to 1.

These assumptions allow the MAU to be calculated using a simple weighted sum of the single attribute utilities:

$$\sum_{i}^{N} k_i U_i(X_i) \qquad (3)$$

where

$$\sum_{i}^{N} k_i = 1 \qquad (4)$$

The MAU metric is commonly plotted against each design's monetary cost to help visualize a tradespace. As the present study is focused on resource usage, however, monetary cost is replaced with the Multi-Attribute Expense (MAE) metric, which captures stakeholder preference on other resource usage in addition to financial cost (e.g., initial operating capability, crew size) through the use of Single Attribute Expense (SAE) functions, akin to the SAU and MAU functions described previously. These preferences are shown in Figure 18.

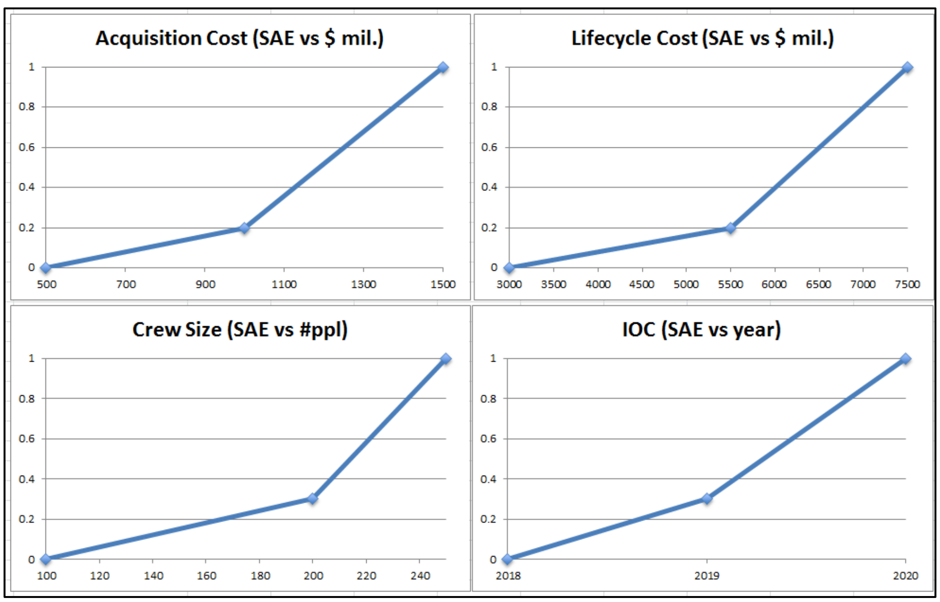

Figure 18. SAE Functions for the Expense Attributes of the NGCS, Where a Value of 1 Represents Complete Dissatisfaction

Note. The "knees" in the curves represent anchoring from similar expenses of previous systems.

For the present study, six representative designs were chosen for evaluation throughout epochs, shown in Figure 19. The resulting evaluations of these designs in the Baseline epoch are shown in Figure 20, which lists all of the attribute values and the resulting MAE and MAU values for each design.

	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	1	2	3	4	5	6
Length (ft)	519	530	440	521	510	562
Beam (ft)	59.8	59	51.1	57.5	56.8	62.2
Draft (cu.ft.)	19.1	18.8	16.3	18.3	20.3	19.4
Prop Type	CRPP	CRPP	CRPP	CRPP	CRPP	CRPP
Hull Material	OS	OS	HTS	HTS	OS	OS
DH Material	Aluminum	Steel	Aluminum	Aluminum	Steel	Aluminum
Def Capability	Low	High	Low	Low	High	Low
Helos	2	1	1	2	2	2
ASUW	High	Medium	Low	Medium	Medium	High
AAW	High	Medium	Low	Medium	Medium	High

Figure 19. The Six Representative Designs (With Corresponding Design Variable Levels) for the Initial Concept Selection of the NGCS

EPOCH: Baseline						
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	**1**	**2**	**3**	**4**	**5**	**6**
Acquisiton	1156	968	627	1011	1009	1230
Lifecycle	5086	4364	3244	4510	4505	5263
IOC	2018	2018	2018	2018	2018	2018
Crew Size	225	230	200	225	220	250
Displacement	7663	8143	4654	7734	8639	9800
Range	4500	6500	4500	6500	8000	6500
Speed	20	20	30	30	30	40
AIR CAP	8	4	2	8	8	12
ENDRNC	50	50	30	45	45	60
SB CAP	60	20	20	60	40	100
MAE	0.36	0.28	0.13	0.29	0.28	0.41
MAU	0.59	0.51	0.31	0.73	0.73	0.90

Figure 20. The Evaluated Attributes of the Six Representative Designs in the Baseline Epoch, With Aggregated MAE and MAU Values

Note. See Figure 2 for units of measurement.

One of the visual results of the MAU and MAE evaluations in the Baseline Epoch is a tradespace plotting the MAU versus MAE metrics for the handful of NGCS designs, shown in Figure 21. These evaluations are performed for all designs in all epochs (a representative six epochs, in the case of the NGCS), providing the metrics necessary for the remaining steps of the method. Different sets of stakeholder preferences on utility attributes were used in addition to those shown in Figure 17, depending on epoch.

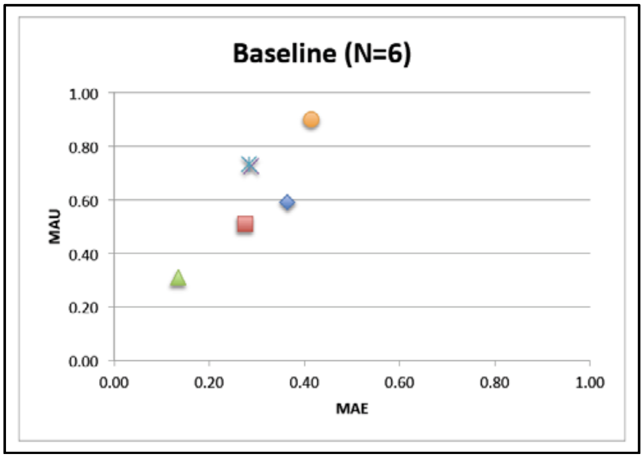

Figure 21. One of the Results of Attribute Evaluation Through the Math Model, Epoch Variable Impacts, and Single/Multi-Attribute Utilities: A Tradespace (MAU vs. MAE) of Six NGCS Designs Operating in the Baseline Epoch

The six epochs evaluated for the NGCS study are shown in Figure 22. They represent all of the 108 possible epochs from the combinations of the epoch variable levels (see Figure 16).

	VUAV	Small Boat Size	Engine Emissions	Range Increase	Ice Region Use
Conflict	Large	35	4	20	High
Mothership	Large	35	2	10	Low
Sojourning	Small	24	2	20	High
Sea Support	Small	35	3	10	Medium
Non-Polluter	Small	24	4	0	Low
Baseline	Small	24	2	0	Low

Figure 22. The Six Representative Epochs Constructed for the NGCS Study (of 108 Possible)

Process 5: Single-Epoch Analyses

Once the evaluations of Process 4 are complete for all designs in all epochs, analysis of design characteristics in single epochs can be performed. In addition to the MAU and MAE metrics, the present case considers the monetary cost of each design as well as each design's Pareto efficiency in the tradespace. This analysis can be repeated for any number of epochs of interest, which can be chosen through various means—those most likely to occur, those most likely to hinder value delivery, or those of concern for other reasons to stakeholders and analysts. The present study chooses only a few of the epochs created in Process 4: Mothership, Sea Support, and Sojourner.

Mothership is an epoch characterized by Large VUAVs and 35ft Small Boats, with a 10% increase in Range of mission over the Baseline Epoch. This combination of epoch variables represents a period in which stakeholders would desire the NGCS to support air and sea operations over non-Arctic waters. The evaluated designs for this epoch are shown in Figure 23, and the corresponding tradespace is depicted in Figure 24.

			Mothership			
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	**1**	**2**	**3**	**4**	**5**	**6**
Acquisiton	1274	1067	691	1115	1112	1356
Lifecycle	6167	5293	3934	5470	5464	6382
IOC	2018	2018	2018	2018	2018	2018
Crew Size	250	255	225	250	245	275
Displacement	7663	8143	4654	7734	8639	9800
Range	4500	6500	4500	6500	8000	6500
Speed	18	18	27	27	27	36
AIR CAP	0	-4	-6	0	0	4
ENDRNC	45	45	25	40	40	55
SB CAP	50	10	10	50	30	90
MAE	0.47	0.36	0.21	0.39	0.38	0.51
MAU	0.38	0.18	infeasible	0.54	0.53	0.75

Figure 23. The Evaluated Attributes of the Six Representative NGCS Designs in the Mothership Epoch

Note. See Figure 2 for units of measurement; negative attribute values are treated as 0.

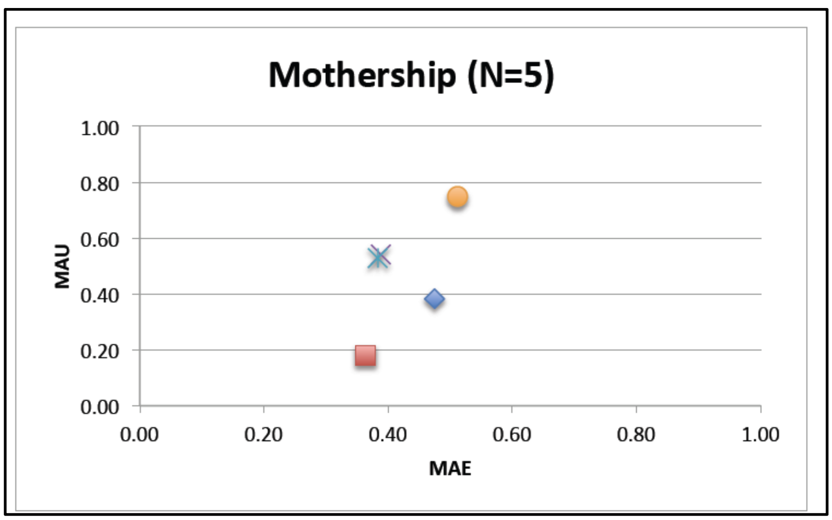

Figure 24. The Six Potential NGCS Designs in the Mothership Epoch

Note. One design is below minimum acceptable utility, leaving the five feasible designs.

It is important to note that in general, the MAU and MAE values cannot be compared between epochs, since stakeholder preferences may change between

epochs (i.e., changed what the 0-to-1 scale represents, as it is not a universal scale). The yields of the tradespaces can always be compared, however, providing the number of designs at or above the minimum acceptable utility and at or below maximum acceptable expense. While six designs were evaluated in each epoch, only five are feasible in the Mothership epoch, indicating that this epoch provides some challenges for at least one potential design (Design #3) to provide minimum acceptable utility and/or operate below maximum acceptable expense.

Because acquisition and lifecycle costs can be limiting factors compared to the other expenses (e.g., crew size) rolled up in the MAE metric, the monetary costs of each design are briefly observed in each epoch of interest. Design #6 has an acquisition cost of $1.3 billion and a lifecycle cost of $6.4 billion, while Design #2 design's acquisition cost is 30% less (~$1 billion), and its lifecycle cost is around 15% less ($5.3 billion). The other designs' costs are in the middle of these two designs. If budget levels were established for the stakeholder in this epoch, those considerations could aid in the comparison of these costs. In addition, Process 6 will examine more informative cost metrics over all epochs, with or without established budget levels.

The Fuzzy Pareto Number (FPN) is a metric developed to indicate a design's relative value in a given epoch, as it measures how far from Pareto-optimality that design lies in the tradespace of that epoch (Fitzgerald & Ross, 2012). Since it represents a percentage of deviation from cost/utility Pareto efficiency, it is measured from 0 to 100; in addition, since it is a percentage, it can be compared across epochs as an indicator of relative efficiency differences. In the Mothership epoch, the FPN for four of the designs is 0 due to their locations on the Pareto front. The remaining design, Design #1, has an FPN number of 20, meaning that it is 20% "inefficient" compared to the Pareto front in this epoch.

These analyses are now briefly discussed for the rest of the epochs of interest.

Sea Support is an epoch during which the NGCS would be required to support extended missions with very capable small boats over a wide range of global waters. It assigns the following values to the epoch variables (various possible levels described in Process 3): Small Boat Size of 35ft, Emissions standards at Level 3, Range Increase of 10%, and High Ice Region Use. The evaluated attributes of all designs are shown in Figure 25; the tradespace of MAU versus MAE follows in Figure 26.

	Blue Diam.	Red Square	Sea Support Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	**1**	**2**	**3**	**4**	**5**	**6**
Acquisiton	1274	1067	691	1115	1112	1356
Lifecycle	5887	5052	3755	5221	5216	6092
IOC	2020	2020	2020	2020	2020	2020
Crew Size	240	245	215	240	235	265
Displacement	7663	8143	4654	7734	8639	9800
Range	3600	5200	3600	5200	6400	5200
Speed	15	15	23	23	23	31
AIR CAP	2	-2	-4	2	2	6
ENDRNC	40	40	20	35	35	50
SB CAP	40	0	0	40	20	80
MAE	0.70	0.60	0.44	0.62	0.61	0.75
MAU	0.14	0.15	infeasible	0.46	0.46	0.71

Figure 25. The Evaluated Attributes of Each Design in the Sea Support Epoch

Note. See Figure 2 for units of measurement; negative attribute values are treated as 0.

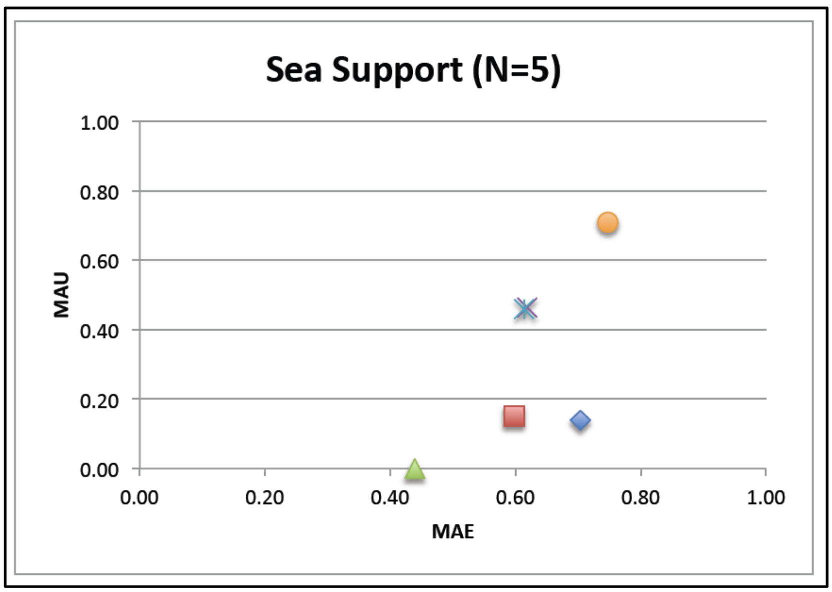

Figure 26. The Four Feasible NGCS Designs in the Epoch Sea Support

The yield of this epoch is, again, five out of the six evaluated designs. From Figure 25, we can see that the acquisition costs are similar to that of the Mothership epoch, but the lifecycle cost is slightly less in this epoch. We can also see that the IOC is pushed back to the year 2020 for all designs. The FPNs for Designs #2, #4, #5, and #6 are, once again, 0, while the FPN for Design #1 is 38.

The third epoch of interest considered, Sojourner, is defined by a Range Increase of 20% plus High Ice Region Use. The stakeholder's preferences in this

epoch are agnostic of the air and small boat capabilities of each design. Figure 27 displays the evaluated attributes of each design in this epoch, and the tradespace of MAU versus MAE is shown in Figure 28.

	Sojourner					
	Blue Diam.	Red Square	Green Triangle	Purple X	Blue X	Yellow Circle
Design #:	**1**	**2**	**3**	**4**	**5**	**6**
Acquisiton	1156	968	627	1011	1009	1230
Lifecycle	6141	5270	3917	5446	5440	6355
IOC	2019	2019	2019	2019	2019	2019
Crew Size	245	250	220	245	240	270
Displacement	7663	8143	4654	7734	8639	9800
Range	3600	5200	3600	5200	6400	5200
Speed	15	15	23	23	23	30
AIR CAP	2	-2	-4	2	2	6
ENDRNC	30	30	10	25	25	40
SB CAP	35	-5	-5	35	15	75
MAE	0.51	0.41	0.27	0.43	0.42	0.55
MAU	0.04	0.33	infeasible	0.23	0.27	0.59

Figure 27. The Evaluated Attributes of Each Design in the Sojourner Epoch

Note. See Figure 2 for units of measurement; negative attribute values are treated as zero.

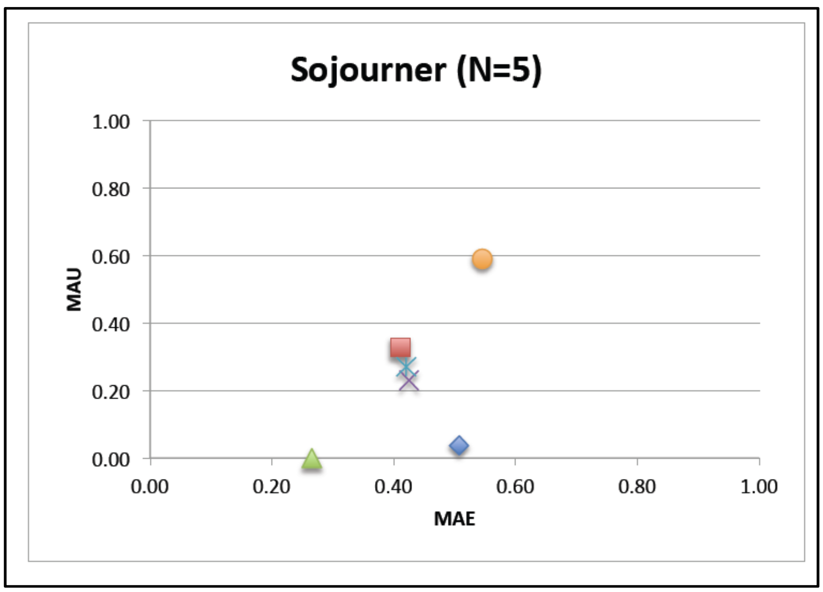

Figure 28. The Five Feasible Potential NGCS Designs in the Sojourner Epoch

The yield of this epoch is five of the six designs; only Design #3 is infeasible. From Figure 27 we can see that the acquisition costs are similar to that of the previous epochs considered, but the lifecycle costs of all designs are around the Mothership epoch's levels. It is of interest to note that only two designs remain on

the Pareto front: Designs #2 and #6. The FPN for Design #4 is 4, the FPN for Design #5 is 3, and Design #1's FPN is 23.

Figure 29 shows each of the six epoch tradespaces of the potential NGCS designs side by side for easier comparison.

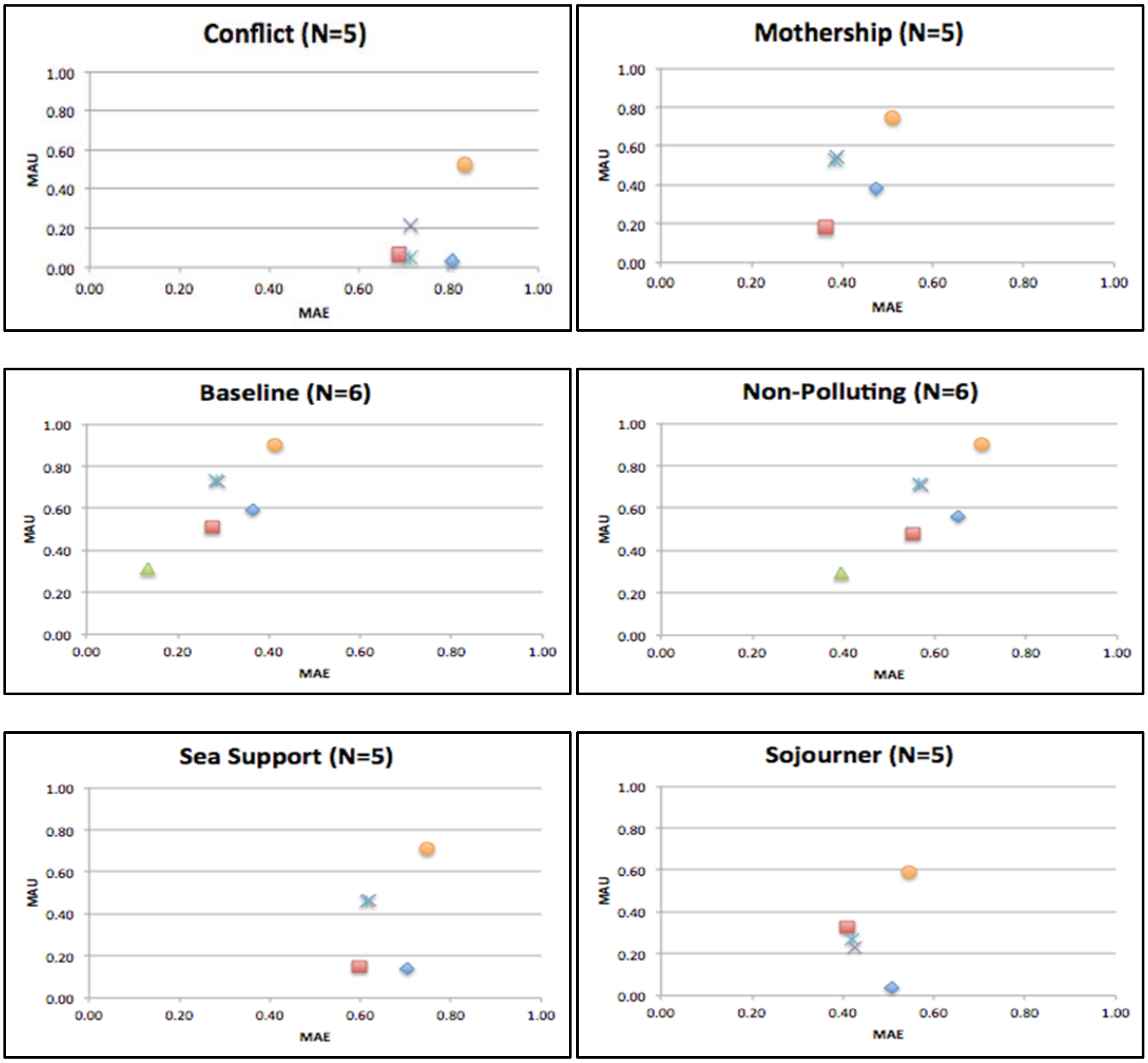

Figure 29. All Six Epoch Tradespaces for NGCS

Process 6: Multi-Epoch Analysis

The analyses of Process 5 can be enlightening regarding the behavior of individual designs and the impacts of individual epochs, but the observations can be time consuming (and the resulting data overwhelming) for any significant number of designs and/or epochs. The analyses can also allow undue weight to be placed on the epochs of interest over those omitted from explicit consideration, even though all epochs represent possible operating environments. For this reason, Process 6 focuses on several summary metrics to gain a higher-level view of all designs'

characteristics over all epochs. Since only six epochs are used as representative of all epochs in this study, these tradespaces are shown side by side for easy comparison in Figure 29. No weight is given to epochs based on likelihood of occurrence, as the purpose of this analysis is simply to cover all possible scenarios the system might encounter. The first of the metrics designed for this purpose is the Normalized Pareto Trace.

The Normalized Pareto Trace (NPT) reflects the percentage of all epochs for which a given design is Pareto efficient (Ross, Rhodes, & Hastings, 2009). A higher NPT indicates higher Pareto efficiency for a design over all epochs, rather than higher Pareto efficiency in only one epoch (like the FPN). It is calculated for any design by counting the number of epochs in which that design has an FPN of zero and then dividing by the total number of epochs. The six potential NGCS designs and their corresponding NPTs across the six representative epochs (shown in Figure 22) are listed in Figure 30.

	Design #	**NPT**
Blue Diamond	1	0
Red Square	2	1
Green Triangle	3	0.33
Purple X	4	0.5
Blue X	5	0.67
Yellow Circle	6	1

Figure 30. The NPTs for the Six NGCS Designs Across the Six Representative Epochs

Note. An NPT value of 1 represents Pareto efficiency in 100% of the epochs.

Clearly, Designs #2 and #6 would be good choices when high priority is placed on Pareto efficiency, as they remain on the Pareto front no matter which epoch is encountered. Design #6 is the most expensive and brings the most utility in every epoch, while Design #2 is one of the lower expense designs and is closer to minimal acceptable utility in most epochs.

The somewhat simplistic measure of NPT can be extended by allowing some "fuzziness" threshold in the evaluation of efficiency. The fuzzy Normalized Pareto Trace (fNPT) is a metric that does precisely this—applies a specified fuzziness percentage to the Pareto front in each epoch, where 0% is a normal Pareto front, and 100% includes the entire range of both the MAU and MAE of the designs in a given epoch (Fitzgerald, Ross, & Rhodes, 2012). The fNPT of each design at several fuzziness levels is shown in Figure 31.

	Design #	0% fNPT	5% fNPT	10% fNPT	20% fNPT
Blue Diamond	1	0	0	0	0.17
Red Square	2	1	1	1	1
Green Triangle	3	0.33	0.33	0.33	0.33
Purple X	4	0.5	1	1	1
Blue X	5	0.67	1	1	1
Yellow Circle	6	1	1	1	1

Figure 31. The Fuzzy NPTs of the Six NGCS Designs for Several Levels of Fuzziness

Note. A value of 1 represents fuzzy Pareto efficiency in 100% of the epochs.

The results of the fNPTs show that with a small amount of fuzziness—around 5%—most of the NGCS designs have maxed out their fNPT number (due in part to the small number of designs considered). Design #1 remains inefficient even after the fuzziness level approaches 20%, decreasing this design's attractiveness compared to the others. With more designs under consideration, the benefits of the fNPT metric should be evident: helping identify designs that may be near-Pareto efficient in many epochs and resultantly missed by the original NPT (such as Designs #4 and #5 in this case).

Aspects of changeability

The metrics shown so far do not take into consideration the possibility of changing from one design to another in a given epoch. This possibility is usually present in some form, however, and as a result it is helpful for multi-epoch analyses to evaluate a design based on the strategies used for change—that is, an original design can be evaluated in multi-epoch analyses by evaluating the target design (to which the original changes, if applicable) in each epoch. Strategies can be defined to guide the change behavior; for the NGCS case, the strategy chosen was "Maximize Efficiency" (i.e., move to the Pareto front if not already there). Transition rules were created such that any design could be discarded and any design purchased in any epoch. A transition matrix was then constructed to reflect the resulting target design (dictated by the chosen strategy) in each epoch from each original design in that epoch. With this additional information on the anticipated transitions and resulting designs in each epoch, modified forms of the previous metrics were constructed and are now discussed.

The effective NPT (eNPT) and effective fNPT (efNPT) metrics evaluate a design across all epochs in the following way: If the change strategy dictates that a (original) design changes to another (target) design in a given epoch, then the target design is evaluated; if the change strategy dictates that a starting design does not change in that epoch, then that starting design is evaluated (Fitzgerald & Ross,

2012). The eNPTs for the NGCS designs, generated by the change strategy "Maximize Efficiency" discussed previously, are shown in Figure 32.

	Design	eNPT	eNPT, with $ budget (notional)	eNPT, with time budget (notional)
Blue Diamond	1	1	0.3	0.17
Red Square	2	1	0.5	0.67
Green Triangle	3	1	0.5	0.5
Purple X	4	1	1	1
Blue X	5	1	0.67	1
Yellow Circle	6	1	1	1

Figure 32. The eNPTs for the NGCS Designs With the Change Strategy "Maximize Efficiency"

As the table shows, most designs' base eNPT is a great improvement over the NPT. In fact, it appears that every design can achieve Pareto efficiency in every epoch. This is true because of the transition rules defined and the transition strategy chosen. Recall that the transition rules defined for the NGCS case state that every design can be discarded and any other design purchased in its place in any epoch, while the transition strategy dictates movement to the Pareto front in every epoch.

If smaller scale changes than discard/replace were available (e.g., "add UAV storage," "remove crew," etc.), rules could be established to represent the feasibility/infeasibility of changing from one design to another in any epoch, thereby limiting the improvement of a design's eNPT over its NPT. Likewise, transition costs of money and time could be defined for any of the transitions between designs, and these costs could be used to limit feasibility (depending on the budget/goal of the transition strategy defined) as well as to track the total expenditures necessary to achieve a given eNPT. In the notional columns on the right of Figure 32, it can be seen that budgets of time or financial costs would prevent Design #1, for instance, from improving very much. Likewise, the other designs may improve or not. (The effective fNPT [efNPT] metric can also be constructed, but is left out of the present study due to the already-maximized eNPT values above.)

Additional aspects of affordability

In addition to the efficiency of a design relative to other designs in each epoch, it can be useful to consider the resource expenditures of a design in various operating environments. Two ways of measuring expenditures across all epochs are applied to the NGCS case: One tracks the maximum amount required of each resource for a given design, and the other tracks the stability of resource consumption throughout all epochs. The first metric can help identify designs that would be unsustainable given the right conditions, while the second metric can

identify designs for which allocating resources in the future (e.g., congressional budget requests) may prove easier due to consistency through changing operational environments. In the case of the NGCS, the highest levels of expense for each design's Lifecycle Cost and Crew Size in all (six representative) epochs are shown in Figure 33.

Max Expense	Design					
	1	2	3	4	5	6
Lifecycle Cost ($ mil.)	7,093	6,087	4,524	6,290	6,284	7,340
Crew Size	260	265	235	260	255	285

Figure 33. The Highest Levels of Lifecycle Cost and Crew Size Across All Epochs

Recalling the Normalized Pareto Trace from earlier, efficient Designs #2 and #6 can be selected for comparison of their respective maximum expenses incurred. While Design #2 could cost a maximum of just over $6 billion in its lifetime, Design #6 could cost over 20% more in one possible scenario. In addition, Design #6 could require 25 more crewmen depending on the epoch encountered. Note that multiple designs' maximum expenses are not all necessarily from the same epoch, as epoch variables impact individual designs differently. (Likewise, with a design's multiple expense attributes, each of a design's attributes are impacted differently by the epoch variables, so that the lifecycle cost may be highest in one epoch, while maximum crew size is required in another.)

The standard deviation of each design's lifecycle cost is shown in Figure 34. Continuing our analysis from the Max Expense, it can be seen that Design #2 has somewhat less variability across epochs than Design #6, by around $400 million. If budget forecasts were known at the time of this analysis, such information could be used effectively to choose a design that fit within the expected variability of the budget for the timeframe of the forecast.

Expense Stability	Design					
(St.Dev. in $ mil.)	**1**	**2**	**3**	**4**	**5**	**6**
Lifecycle Cost	2,156	1,850	1,375	1,912	1,910	2,231

Figure 34. The Standard Deviation of Lifecycle Cost for Each Design Across All Epochs

These considerations, when combined with previous analyses, help outline the impact of the risks involved for any initial concept selection, and they can help analysts and decision-makers alike understand the traits behind design concepts that would be affordable in all futures.

Process 7: Era Construction

The analysis up to this point has evaluated NGCS designs in epochs, or short-run periods of fixed contexts and needs. By combining these short-run fixed periods into a sequence over a longer period of time, an era is created—allowing a practitioner to study the attributes of designs over one possible development of the operating environment, as well as the effects of path dependence through epochs (Ross & Rhodes, 2008). Two eras were manually constructed for the present study, each representing a 10-year sequence of epochs that the NGCS may encounter (taken from the six representative epochs from Process 4, c.f. Figure 22). The first era considered consists of the following sequence:

> Baseline (36 months), Sea Support (36 months), Baseline (24 months), Non-Polluting (24 months).

The second era considered consists of

> Sojourning (24 months), Conflict (36 months), Mothership (36 months), and Sojourning (24 months).

Process 8: Single-Era Analyses

The first era comprises epochs in which stakeholder preferences do not change. As a result, the MAE and MAU values can be compared directly. The era is shown in Figure 35 (each tradespace) and Figure 36 (line graph view).

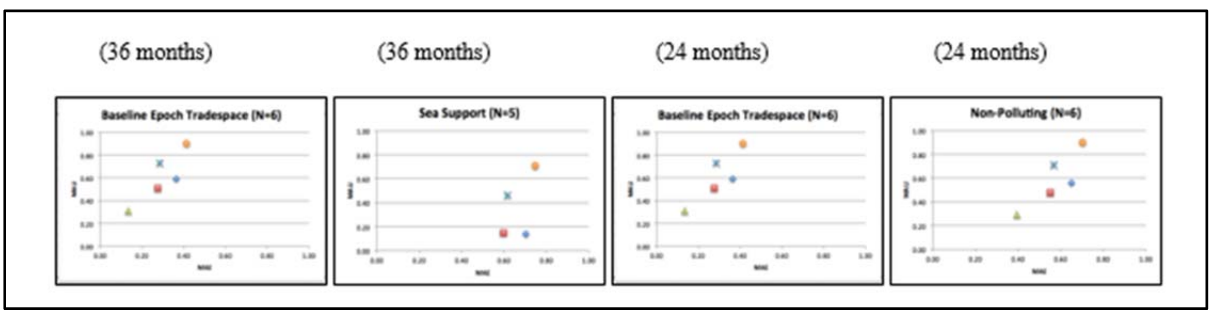

Figure 35. The Four Epochs of Era #1 and Their Durations
Note. Stakeholder preferences remain constant; as a result, MAU and MAE values can be directly compared across epochs.

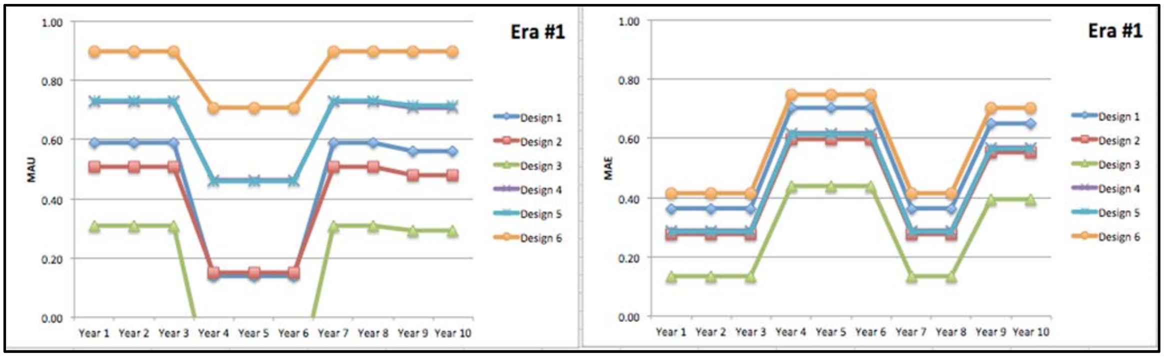

Figure 36. Left: The MAU Values of Each Design During Era #1; Right: The MAE Values of Each Design in Era #1

Before proceeding, it should be noted that Design #3 is infeasible in the Sea Support epoch, meaning that design cannot provide minimum acceptable utility throughout this era. If a decision-maker believes this era to be one of the more likely narratives to play out for the NGCS, then that design should be removed from consideration.

Using the concept of time value of money, the NPV of each design's operations cost can be calculated for the entire era. (To obtain the operations cost for a given timeframe, the acquisition cost was subtracted from the 30-year lifecycle cost, and the result divided into the appropriate number of months.) For instance, Design #1's yearly operations cost in the Baseline Epoch is $131 million; this amount is used as the input to the final NPV calculation. This same calculation is performed for each design in each epoch in the era, and a 10% discount rate is assumed. The intermediate values and final calculation are shown in Figure 37.

Era #1

($ millions)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
NPV Ops Yr. 1	131	113	87	117	117	134
NPV Ops Yr. 2	119	103	79	106	106	122
NPV Ops Yr. 3	108	94	72	96	96	111
NPV Ops Yr. 4	116	100	77	103	103	119
NPV Ops Yr. 5	105	91	70	93	93	108
NPV Ops Yr. 6	95	82	63	85	85	98
NPV Ops Yr. 7	74	64	49	66	66	76
NPV Ops Yr. 8	67	58	45	60	60	69
NPV Ops Yr. 9	59	51	40	53	53	61
NPV Ops Yr. 10	54	47	36	48	48	55
NPV Total:	**929**	**803**	**618**	**827**	**826**	**953**

Figure 37. Calculation of the Net Present Value ($ Millions) of Designs' Operations Costs for Era #1

From these numbers, it appears that Designs #2, #4, and #5 form one group with similar NPV operations costs, and that Designs #1 and #6 form another similar

group. While these numbers reflect the same grouping of designs as the MAE suggests in the tradespace plots, it is important to note that the MAEs could be similar for certain designs whose operations cost's NPV are vastly different. For this reason, it can be necessary to consider these costs separately from the MAE score itself if information about the operations budget is known at this stage.

The additional affordability considerations from Process 6 can also be repeated at this point: The maximum values of the operations costs of each design are shown in Figure 38, and the standard deviation of operations costs throughout the era is shown in Figure 39.

($ million / yr)	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**	**Design 6**
Max Ops Cost:	154	133	102	137	137	158
Max Ops Cost (NPV):	131	113	87	117	117	134

Figure 38. The Maximum Yearly Operations Cost of Each Design Throughout Era #1, Compared With the NPV Maximum Operations Cost

(St.Dev. in $ mil.)	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**	**Design 6**
Expense Variability:	11.0	9.5	7.1	9.8	9.8	11.4

Figure 39. The Standard Deviation of Each Design's Operations Costs Throughout Era #1

In this case, the results from the era analysis reflect the same conclusion as Process 6 (over all epochs): The more expensive designs have slightly more variance than the less expensive designs. If more designs were under consideration, it may be possible to find a more expensive design that is more cost-stable across all epochs (and/or in a particular era), which may give incentive to include it when considering designs for final selection. Of course, these metrics can be considered for any resources of particular concern but are only applied here to operations cost for demonstration purposes.

The second era, shown in Figure 40 consists of epochs with changing stakeholder preferences, and so the MAU and MAE values cannot be compared directly across epochs.

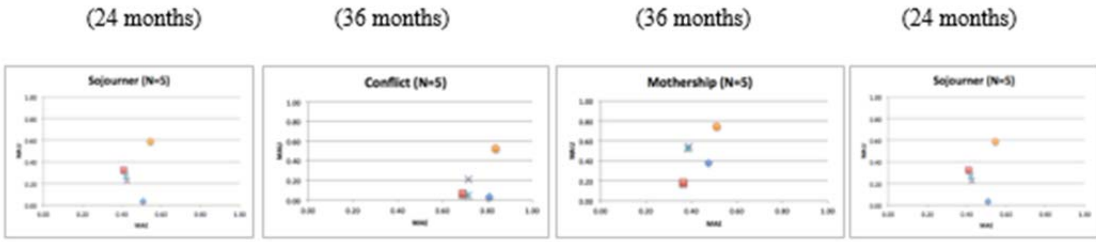

Figure 40. The Four Epochs of Era #2
Note. The MAU and MAE values cannot be compared between epochs due to changing stakeholder preferences.

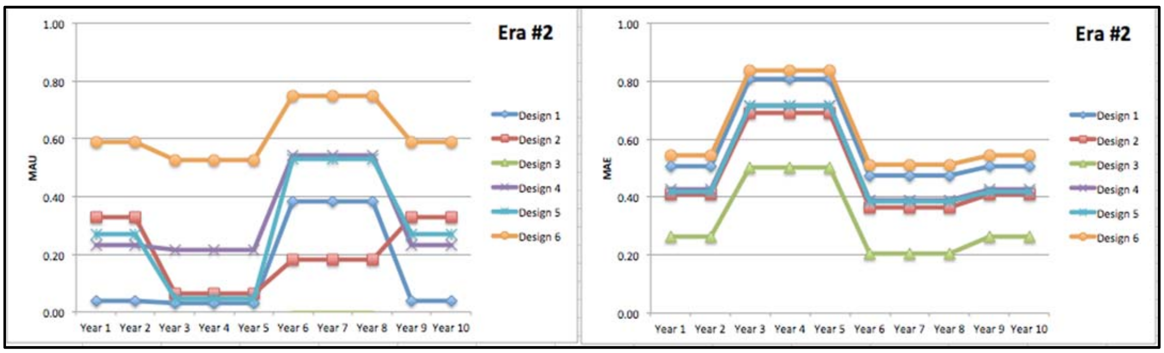

Figure 41. Left: The MAU of Each Design Through Era #2; Right: The MAE of Each Design During the Same 10-Year Period
Note. Stakeholder preferences change between epochs.

It is again noted that Design #3 is infeasible in this era; in fact, it is not feasible in even one of these epochs. Design #2, while starting the era highly ranked in the MAU measurement, makes its way to the least favorable ranking for a short time. Its expenses remain least dissatisfying, however, among feasible designs in this era. The NPV calculations for all designs in this era are shown in Figure 42.

Era #2						
($ millions)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
NPV Ops Yr. 1	166	143	110	148	148	171
NPV Ops Yr. 2	151	130	100	134	134	155
NPV Ops Yr. 3	157	135	104	140	139	161
NPV Ops Yr. 4	143	123	94	127	127	146
NPV Ops Yr. 5	130	112	86	115	115	133
NPV Ops Yr. 6	101	87	67	90	90	104
NPV Ops Yr. 7	92	80	61	82	82	95
NPV Ops Yr. 8	84	72	55	74	74	86
NPV Ops Yr. 9	78	67	51	69	69	80
NPV Ops Yr. 10	70	61	47	63	63	72
NPV Total:	**1171**	**1011**	**774**	**1042**	**1041**	**1204**

Figure 42. Calculation of the NPV Operations Costs of Each Design in the 10-Year Era #2

It should be obvious that this era represents a particularly challenging environment for the designs, with two of them exceeding one billion dollars for the NPV operation costs. The maximum values and the standard deviations of operations costs for all designs are shown in Figure 43 and Figure 44.

($ million / yr)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Max Ops Cost:	190	164	125	169	169	195
Max Ops Cost (NPV):	166	143	110	148	148	171

Figure 43. The Maximum Operations Cost Incurred by Each Design Throughout Era #2, Compared With the Maximum NPV Operations Cost

(St.Dev. in $ mil.)	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Expense Variability:	11.5	9.9	7.6	10.2	10.2	11.8

Figure 44. The Standard Deviation of Operations Cost Throughout the 10 Years of Era #2

Process 9: Multi-Era Analysis

While certain insights can be gained by inspection of individual eras such as those in Process 8, it is also instructive to observe alternatives' behavior across the era space (i.e., in many or all of the eras constructed by Process 7) since large numbers of eras can be constructed through combinatorics, probabilistic state transitions, and other means. Process 9 focuses on the analysis across many eras, which are somewhat analogous to the Multi-Epoch Analysis of Process 6.

Most of the metrics of Multi-Epoch Analysis carry over, including the NPT, fNPT, eNPT, efNPT, and Expense Variability, with slight differences in calculation. For example, the NPT/fNPT of each design in an era are calculated using only the epochs in that era, and a Pareto trace can also be calculated as a time-weighted average across the era. Once calculated for each design in each era, the NPT values can be compared in various ways. One could look for the extreme NPT values, whether high or low, leading back to Process 8 and observation of the properties and interactions of the specific design and era that cause these extreme values. (In the NGCS case, for example, it might be discovered through this activity that Design #3 performs very poorly in eras with long durations of the Conflict epoch. Further investigation could lead to the insight that the lack of UAV capacity drastically reduces satisfaction in eras involving Conflict.) One could also look for the highest average NPT over all eras to identify a design that consistently delivers value across all identified possible futures.

The effective versions of the NPT and fNPT can become more informative in this process as well. Because transition rules and costs can depend directly on contextual uncertainties (whether epoch variables or stakeholder needs), the eNPT/efNPT metrics can help identify path-dependent weaknesses of particular change strategies. The eNPT/efNPT metrics of Process 6 only considered transition costs and rules for one epoch, but analyzing these same metrics through sequences of epochs can reveal particularly devastating (or beneficial) contextual developments. For example, in the NGCS case, assume Design #3 started in the Baseline epoch, followed by a change to Design #5 in the Mothership epoch based on the rule “Maximize Efficiency.” That sequence appears to satisfy stakeholder needs very well relative to the other designs. If the Mothership epoch were followed by the Conflict epoch, however, and no change was allowed from Design #5 to any design on the Pareto front—whether due to the transition budget or established transition rules—the eNPT of Design #3 in the era would be resultantly lower (how much lower depends on the duration of the epochs and era). This consequence is only one example of many path-dependent behaviors that emerge from the incorporation of change strategies over the long run.

As noted, the Expense Variability metric can also be applied during this process, identifying contextual sequences that provide for either stable or turbulent expenses relative to other eras. The goal of all the analyses of Process 9 is to identify those designs and change strategies that result in efficient value delivery at low and stable costs throughout the entire system lifecycle.

Discussion of Impact on Development Cycle

The epoch variables analyzed thus far in the current study have focused primarily on the post-acquisition phases of the system lifecycle (e.g., technology

levels of UAVs, emissions regulations, mission parameters). One natural extension of the EEA approach is to model the epoch variables of the development cycle itself—that is, to model each stage of development in one or more possible epochs comprised of budget level, material and labor availability, political relations, and so forth. Example epoch variables in such a study are shown in Figure 45.

Notional for Development Cycle		
Epoch Variable	**[Range]**	**Units**
Subsystem1	[4,6,8]	TRL Level
Labor available	[Nominal, Low]	Level
Acq. Budget	[80%,90%,100%,110%]	Baseline Adj.
Ops Budget	[80%,90%,100%,110%]	Baseline Adj.

Figure 45. Example Epoch Variables With Notional Ranges for Describing Development Cycle Environments

In the example variables shown in Figure 45, several types of resources are modeled: subsystem availability, labor, and budgets. These types of variables could be modeled at any level of detail desired—instead of an overall budget number, for example, colors of money could be used to represent specific capability or operations. The epochs formed by the combinations of these variables' levels could then be sequenced, creating eras describing possible developments of the environment throughout preliminary design, detailed design, and construction/production. Such an approach could efficiently encapsulate much of the uncertainty present throughout the long development lives of major systems and programs.

This encapsulation would provide several strategic benefits for decision-makers. First, it would allow easy identification of systems that require total commitment—those with no adequate "fall-back" plan in the case of falling budgets, infeasible subsystems, or other resource perturbations that might occur before the system production and use. Second, and inversely, it would help identify system choices that would limit expansion of quantity or capabilities, should such expansion be desired in the case of a new threat or political development (e.g., the increasing budgets in Figure 45). Third, decision-makers could potentially identify the common capabilities of a number of highly desirable systems, allowing production of those core capabilities to begin while deferring the final configuration decisions until later in the development cycle, when the system's initial operational context can be more accurately determined.

Affordability Insights

As noted in the introduction to this case, the application of this design method directly informs the analysis of system affordability for the potential NGCS designs.

By using the MAE function, the stakeholder preferences on various resources are combined: development schedule (IOC) with monetary (e.g., acquisition and lifecycle) and non-monetary (e.g., labor) expenses. Using this metric, it can be seen that Designs #2, #4, and #5 all have similar resource expenditures in most epochs, while Designs 1 and 6 are somewhat higher. This measurement alone could provide a good starting point for selecting Designs #2, #4, and #5 as designs of interest. The Max Expense metric from Process 6 shows that Design #2 could require slightly more crew (265) than Designs 4 and 5 (260 and 255), but Design #2 could also cost less (albeit not by much) over its lifecycle ($6.1 billion vs. $6.3 billion). Finally, the Expense Variability metric from Process 6 shows that these designs' expenses vary in similar ways over the epochs. Since all three of these designs appear to be affordable alternatives, other measures (such as stakeholder satisfaction) can be used to further restrict the number of designs under consideration. Observing Design #5's drop in utility in the Conflict epoch (see Era #2, for instance) could result in it being removed from consideration, since it has the same level of expense as Design 4, which has more stable value delivery throughout Conflict and other epochs. Designs #2 and #4 can be further examined, then, to identify the design variables and attributes that enable these to be affordable choices in the design of the NGCS system. For example, both designs are a length of 520–530 feet with medium levels of Anti-Surface and Anti-Aircraft capabilities. These common traits could be further investigated to gain insight into the interactions between these particular variables, the ship attributes they most influence, and the stakeholder preferences on those attributes. In this way, the affordability analysis performed through the application of this method leads into a study of the common traits of affordable NGCS solutions. Rather than pointing to one solution deemed "most affordable," this approach provides stakeholders with a new perspective on the affordability of systems during the conceptual design phase, allowing them to better understand the complex behaviors of the system across environments as well as the trades at play.

Discussion

As affordability remains a relatively new ility, there are many variations of its definition and analysis. Most definitions of affordability are concerned with the balance of performance, cost and schedule needs, and constraints over the system lifecycle. However, unlike other system ilities, performance is no longer regarded as *sine qua non* in affordability considerations. In the paradigm of designing for affordability, systems are not only architected for performance and risk mitigation, but also with explicit cost and schedule considerations. Affordability has emerged as a high priority ility that directs the early stage design process towards developing systems with greater cost effectiveness and schedule effectiveness. Recent management failures in high-profile defense programs have further underlined the

importance of affordability considerations during early-phase design. This motivates the research on a method for affordability tradeoffs under uncertainty.

An important task within the conducted research was a literature study, along with interviews of selected experts. This included reviewing various definitions and analytic frameworks that have been proposed to incorporate affordability considerations into current systems engineering practice. Despite advances in the literature, two key challenges were identified in formalizing a paradigm of designing for affordability:

1. **Lack of an accepted definition and a set of guiding principles for affordability within the systems community**. This challenge has resulted in a plethora of proposed affordability approaches, with a difficulty in directly comparing these approaches due to underlying differences in the meaning of what makes an "affordable" system. Once a common definition and a common set of principles for affordability are identified by the community, efforts can be made to integrate approaches taken by the government, industry, and academia into a concerted effort for reducing overall program costs and schedule slippages.
2. **Absence of mature metrics and systematic frameworks for comprehensive affordability analysis**. Traditional cost-related metrics have been proposed for affordability analyses, but have been deemed insufficient to encompass the broader intent of current design for affordability efforts. Other metrics, such as the use of a multi-criterion cost function, are less mature and warrant further study to test for generality and feasibility in actual practical analyses. A systematic framework with an accompanying set of metrics would enable affordability analysis to be conducted consistently and more holistically than just simply extending prior practice (e.g., analysis must include aspects of acquisition cost, operations and maintenance cost, development schedule, upgrade schedule, externality costs, and available budgets, all over time).

While performance is easily quantified through technical specifications, cost and schedule are much harder to measure objectively and accurately. Many quantitative methods have been proposed to conduct affordability analysis, ranging from probabilistic estimates of cost and schedule risk to setting either cost or time as independent variables during engineering tradeoffs. In the search for affordable solutions, this research proposed the use of tradespace exploration–related methods to facilitate the selection and identification of architectures that best fit cost and schedule requirements of stakeholders. The *Multi-Attribute Tradespace Exploration*

(MATE) method can be used to perform such affordability tradeoffs, as it allows the capturing of stakeholder preferences for simultaneous multiple objectives.

MATE resolves conflicting and subjective evaluations of decision-making processes by combining various single-attribute utility functions for every attribute of interest into a single function that quantifies how a decision-maker values different attributes relative to one another. To effectively evaluate the impact of dynamic variation in costs with tradeoffs in decision parameters and time to completion, this research has applied Epoch-Era Analysis (EEA), as this method considers and clarifies the effects of changing contexts and needs over time on the perceived value of a system in a structured manner. Instead of discretizing the system lifecycle according to traditional system milestones, EEA discretizes the lifecycle according to impactful changes in the operating environment (e.g., available budget), stakeholders, or the system itself, through the constructs *epochs* and *eras*. Epochs represent time periods with fixed contexts and needs, while eras are sets of sequentially ordered epochs. This method would allow for the consideration of changes to a system throughout multiple possible alternative lifecycles and allow for the identification of systems that are potentially more efficient in resource costs.

In the application of these methods, this research has proposed the use of a new metric, Multi-Attribute Expense (MAE), to quantify acceptability of resource usage, where resources include multiple distinct criteria including cost and time parameters of a system. An MAE function assigns weights to different cost and time parameters in the same way as a multi-attribute utility function. The MAE metric reflects the degree of stakeholder satisfaction with resources expended in the design or operation of a system. Augmented by resource metrics, MATE and EEA can be combined to form a systematic method for architecting affordable solutions since achieving affordability requires good decisions both upfront (MATE), as well as across the lifecycle (EEA). This method has been applied to a case study involving the design of a next-generation combat ship (NGCS) to validate the method's feasibility.

As shown in the NGCS case study, the application of the proposed method leads to some salient points about affordability analysis in the conceptual design phase. First, capturing expenses as attributes preserves stakeholder and model information, as opposed to losing information through monetization of non-monetary expenses (e.g., dollars per ton CO_2). For example, Years to Initial Operating Capability (IOC) of each NGCS design is not easily converted to a monetary amount, but it can be successfully incorporated into the MAE. The second point is that using EEA can facilitate better understanding of a design's affordability over its entire lifecycle, as practitioners can quickly discern how expensive an alternative might be with regard to levels of resource usage (i.e., Max Expense) as well as how

resource usage may change across multiple epochs and multiple eras (i.e., Expense Variability). If budget levels are established *a priori* for acquisition costs, operating costs, labor usage, development schedule, or other expenses, the Max Expense and Expense Variability metrics can be compared against those levels to identify affordable solutions. In the absence of any established levels, potential designs can still be compared against one another in the tradespace.

Through this method's approach to tradespace exploration and epoch-era analysis, decision-makers can be more informed of the risks associated with each potential design's resource needs, and hence gain further insights into each potential design's affordability relative to other available alternatives.

This research project has made progress in addressing the two challenges identified in the literature review and conversations with selected experts: lack of accepted definitions and lack of metrics with systematic framework.

Lack of accepted definitions. The first challenge identified in this research is the lack of accepted definitions. The research met this challenge through the following:

- **Proposed a definition for affordability.** After identifying the major themes in affordability analysis and considering them in light of related analysis approaches, affordability can be defined as *the property of becoming or remaining feasible relative to resource needs and resource constraints. Resource needs* are the cost and schedule preferences elicited from stakeholders, and *resource constraints* are the external restrictions imposed upon these preferences that limit the range of feasible solutions. *Feasible* here means not violating acceptability bounds, which include both constraints and minimum acceptable need levels. For example, a program may desire a $100 million unit cost per vehicle, while given a budget of $300 million. If the unit cost is less than $100 million, that is better for the program. In fact, the program prefers that the unit cost is a low as possible. In this particular case, the system affordability increases as it remains below $300 million and unit costs drop. As systems and operating contexts are dynamic, resource needs and resource constraints may change over time, therefore affordability for a given system may change as well.
- **Proposed a definition for an affordable design solution.** Given the above definition of affordability, an *affordable design solution* is one that is feasible when it fulfills resource needs and functions within the resource constraints for a fixed context. As contexts change, a particular solution may remain in, enter, or exit the feasible set of

solutions. Affordable solutions are those that remain in or enter the feasible set of solutions.

- **Proposed affordability analysis to be conducted via the identification of solutions that remain affordable for part (short run) or all (long run) of the system lifecycle.** With this guiding principle, an affordable solution that is identified will be capable of satisfying possible changing resource requirements and resource constraints over the system lifecycle. Affordability can then apply to both short term (meeting affordability bounds across one or several contexts) as well as long term (meeting affordability bounds across many or all experienced contexts).

Lack of metrics with systematic framework. The second challenge identified in this research is the lack of metrics with a systematic framework. This is how the research addressed that challenge:

- **Proposed method incorporating MATE, EEA, and MAE to conduct affordability analysis.** The research has leveraged related existing methods to address the challenges identified in the literature, including systematic consideration of alternatives during up front system selection (MATE), throughout operations and maintenance (EEA), as well as through the incorporation of a multi-criteria perspective on resource use (MAE).
- **Applied method to demonstration case (NGCS).** This research has applied the proposed the method to the NGCS case study as a preliminary validation of the method's feasibility.

Existing methods for conducting affordability analysis are relatively new, and the application of expense functions and tradespace exploration methods constitute yet another proposed approach to search for affordable solutions. The addition of another definition and another affordability method does not solve the upfront pair of challenges identified, but rather adds to the potential solution space for what may be most useful to the community. This research constitutes a step in trying to synthesize some of the key themes discussed by the community, while proposing an alternative approach that does not rely solely on cost-modeling techniques. Further work to validate, refine, and socialize the concepts in this research are essential for fostering consensus in the community.

While the application of this new method has been demonstrated in a simple case study, it has yet to be extended to more complex case studies with much larger sets of design solutions. It could be useful to validate the proposed method using

additional case studies, as well as to conduct a method comparison of this approach to other existing approaches.

Following the research conducted in this project, a number of potential next step activities have been identified:

- **Extending the method to more complex case studies with more design solutions.** To ensure that affordability analysis can be conducted more comprehensively, research should be done to validate the feasibility of the method in a wider variety of real-world applications.
- **Extending affordability analysis from a system to a project, program, and portfolio.** As a project, program, and portfolio can differ greatly in terms of both scale and scope, affordability analyses conducted at these levels cannot only derive affordable architectural solutions, but must also generate recommendations for affordable acquisition strategies and policy implementations.
- **Exploring the relationship of affordability with other system ilities like flexibility and survivability.** Research can be done to identify affordably changeable or affordably survivable solutions by revisiting case studies previously conducted for the understanding of the aforementioned ilities. Quantitative metrics for flexibility and survivability can be used in concert with the newly proposed affordability metrics and analysis method for affordability.

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